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A Comparative Approach on Successive vs Simultaneous Drilling

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Abstract. This work presents research on the two possible ways to machine multiple holes on the same part, arrayed placed. The problem is approached from the economical point of view. The objective is to provide a tool able to help in choosing the best solution, either in terms of expenses, or of processing time, when making the decision on the manner of machining groups of holes by drilling: successively, or simultaneously. This is a complex task since many variables are involved in calculating the costs and/or machining time in such a case. The output of the research is an algorithm used to perform calculations, and what is more important, two software tools that allow the user to compare the result of any of the two ways to proceed, in economic and technological terms, based on the input data which characterize the process. The effect of variation of a certain input on the output can be, as well observed easily by using the graphical software tool. The general conclusion is that in most cases the simultaneous drilling is more effective, but it might involve bigger costs of hardware than the successive method. If the total cost is the criterion to appreciate the results of manufacturing, the simultaneous machining is the best for the big batch size. One of the soft-ware tools presented can determine the minimum batch size for which simultaneous machining is better. Anyway, the final decision is made by the technological designer, considering the main criterion of appreciation, and being guided by the output provided by the software tools.

Keywords: successive drilling · simultaneous drilling · metal cutting · cost of drilling · drilling time computing

1 Introduction

The problem of simultaneous drilling is very common in the field of drilling for mining, geothermal resources, gas, and oil, being approached since long time ago [1, 2], until nowadays [3, 4]. While in the mentioned areas the process of drilling is a (very) long lasting one, of course, drilling successively is not at all an option. That is why the cited works focus on aspects such as vibrations, effectiveness of the drilling, side effects and other. Simultaneous drilling is applied in metals machining, as well. Most of the scientific research targets the technological aspects including tool-life, cutting conditions, quality

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of surface, cutting (input) parameters like helix angle, spindle-speed, feed rate, output – surface roughness, cutting forces, temperature, but not limited to the mentioned ones. The trials were conducted on different materials, and, in some cases, a comparison between single-hole drilling and multi-holes drilling was carried out.

In literature are described research on behavior of an aluminum alloy under the different conditions of multi-drill and single-drill machining [5]. The general conclusion was that multi-drilling is to be preferred against single-hole drilling in terms of all the aspects studied. Paper [6] presents a study that aims at the process optimization of drilling a composite material Al-6063/TiC, an Al-6063 alloy reinforced with 15% titanium carbide. In [7] three different aluminum alloys are investigated in terms of their behavior under multi-drilling conditions and their effects on the quality of machined surface, cutting force, and influence on tools wear. Each of the alloys displayed better results on the different aspects investigated. Optimization of machining parameters at multi-drilling the Al5083 for aerospace purposes. Is discussed in reference [8], where is presented how Taguchi method and Fuzzy logic approach are used to conduct the research. The adequacy of the tool material and geometry to multi-drilling process is studied in [9]. The research was conducted for Al2024 material, widely used in aerospace applications, that suppose many holes to be machined on the same part, for assembling purpose. The conclusion was that the carbide drills having a high point angle were most suitable and produced the best quality of holes surface. The shorter chips prevent to a certain extent forming the built-up edge.

Despite the variety of subjects approached, related to simultaneous multi-drilling, all of them were concerned with technical aspects, with no reference related to economic aspects of the problem. In this context, by economical aspects, one means the expenses involved in manufacturing, and mainly making the decision on which of the processes are cheaper when it comes to simultaneous vs successive drilling the groups of holes. The present paper analyses the factors that must be taken into account when calculating the costs of multi-drilling, and the way they act on the expenses. A case study illustrates how the method works, and to what extent a slight variation of one input can decisively affect the output.

2 The Problem

When manufacturing parts which display several parallel and geometrically identical holes, an important decision that must be made is how to machine them: simultaneously, or successively. To compare the results of simultaneous and successive drilling, two main criteria can be considered: the total cost of machining (hardware consumed), and the effectiveness (total time) required to manufacture the entire batch. In terms of effectiveness, the decision seems to be easy to be made, without any calculation, since roughly, multi-drilling shortens the total machining time n times, n being the number of holes machined at a time.

In terms of expenses, the problem is much more complicated, because calculating the cost of machining the groups of holes either simultaneously or successively involves many variables. Among these may be mentioned the size of the batch, the type, material, cost and (total) tool-life of a drill, costs of supplementary devices if they are needed, and others.

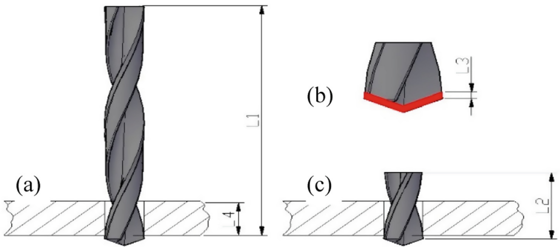

Fig. 1. The main dimensions (lengths) of the drill. (a) the new drill, (b) the length of the drill removed when re-sharpening (c) the drill at its end of tool-life

3 Solving the Problem

3.1 Variables Involved in Cost and Time Calculation

As already briefly were enumerated above, the variables involved in calculating the costs, are here explained, and where needed are presented the calculating formulae, as well. The way the formulae are structured, make them equally applicable both for successive and simultaneously machining the group of holes on a part. The difference is given by the specific input data.

Common variables for the simultaneous and successive machining. Several values are involved in finding out the result of the problem. The next ones are used, and have the same meaning, regardless the manner of machining the holes: simultaneously, or successively.

- d, the diameter of the hole (drill) [mm];
- p, the price of a drill [mu] (monetary unit);
- L1, the active length of the drill [mm];
- L2, the length of drill at its end of life [mm];
- L3, the length of the drill removed when re-sharpening [mm];
- L4, the depth (length) of the hole [mm];
- T, tool-life of a drill [min];
- Bs, the batch size [pcs];
- Np, the number of holes/part [pcs];
- v, cutting speed [mm/min];
- s, the feed-rate [mm/rev].

Some of the dimensions mentioned above, as features of the drill are shown in Fig. 1.

Specific Variables for Simultaneous Machining. Some symbols address only the simultaneous machining. They are presented below:

- ngs, number of holes machined simultaneously [pcs];
- Pd, price of the multi-spindle head [mu] (monetary unit);

Specific Variables for Successive Machining. N/A, that is no other supplementary variables are necessary to describe the specific of the successive machining of the holes on the same part. Note that *ngs* in this case is 1.

Some Calculated Values. Using as input the above presented data, some specific values are calculated. They lead to the final output, the cost of manufacturing the entire batch, in the successive, and respectively simultaneous machining of the holes. Also, the total time to manufacture the entire batch is provided as an output.

To get to the final output, first must be calculated the spindle speed depending on the drill diameter and the desired cutting speed - Eq. (1), then the machining time of a hole - Eq. (2), some specific features of the drill - Eqs. (3,4), the number of resharpening that can be applied to a drill - Eq. (5), the number of holes that can be machined by a drill until it ends its total tool-life - Eq. (6), and the number of drills necessary to machine the entire batch - Eq. (7). The final output consists of the total cost of the hardware used (drills and multi-spindle head – if necessary) - Eq. (8), the total time spent to manufacture the entire batch - Eq. (9), and the total cost of machining the holes -Eq. (10).

$$N = 1000 * v / pi / d \tag{1}$$

$$Tb = (L4 + 1) / (n * s) \tag{2}$$

$$L2 = L4 + 10 \tag{3}$$

$$L5 = L1 - L2 \tag{4}$$

$$Nr = L5 / L3 \tag{5}$$

$$Gd = T * Nr / Tb \tag{6}$$

$$ND = round\,(BS * NP * ngs + 0.5) / Gd \tag{7}$$

$$TC = Pd + p * ND \tag{8}$$

$$Tt = BS * NP * Tb / ngs \tag{9}$$

$$Cost = TC + Tt * Cmm \tag{10}$$

[1]the value 1 is added to L4 only if the hole is pierced. If yes, this is 1mm, the value the drill overcomes the bottom of the hole, to ensure the detaching of the chip.

[2]The value of 10 is the length needed to ensure the evacuation of the chips at the top of the part.

where:

n= spindle speed [min^{-1}];

Tb= time spent to machine the hole(s) on a part [min];

L2= length of the drill at his end of total tool-life [mm];

L5= useful length of the edged side of the drill (the length of the drill that can be used to machine the hole) [mm];

Nr= number of possible re-sharpening of a drill, dimensionless;

Gd= number of holes that can be machined by a drill until it ends its total tool-life [pcs];

ND= necessary number of drills to manufacture the entire batch [pcs]; note that the number of drills needed to process a hole must be rounded to the next integer value. In the case of simultaneous machining several holes, the number of drills first is rounded, and only afterwards is multiplied by the number of holes machined simultaneously.

TC= total hardware expenses (multi-spindle head, and drills) [mu] (monetary unit);

Tt= total time spent to manufacture the entire batch (total machining time);

Cmm = expenses to use a machine-tool for one minute;

Cost = the total cost of machining the holes, which sums the hardware expenses (TC) and the cost of exploiting the machine-tool. This component of the expenses is given by the total machining time (Tt) multiplied by an indicator specific to each machine tool. This reflects synthetically all the expenses involved in exploiting the equipment (energy, consumables, personnel expenses, and others).

The given equations cannot provide a clear picture of the problem, so it is considered that some case studies can illustrate much better the influence of some input parameters on the result, and help make the decision, according to the criterion considered.

4 An Alternative Approach

Another way to approach the problem is to determine the range of batch size for which the successive or simultaneous way of machining is the less expensive one. This can be done by two different methods:

- **Graphically**, representing the total cost as a function of the batch size for the two ways of machining, and observe the point where the two graphs intersect;
- **Analytically**, by equalling the formula of computing the total cost for the two machining ways. All the inputs are considered known, except the Batch size. The solution of this Eq. (11) is the batch size where the less expensive machining method shifts to the other one.

4.1 Graphical Method

To solve the problem graphically, a piece of software was developed in a programming language that offers high capability in terms of graphics.

Input values are delivered to the program that computes the required data to draw the two graphs. For each machining method the number of points the graphic is drawn through can be controlled by means of an input. The intersection of the two graphics delimitates the two domains in which a method is better in terms of costs than the other one, as can be seen in Fig. 2. The main drawback of this method is that it is quite difficult to appreciate accurately the value of the cost where the two graphs intersect.

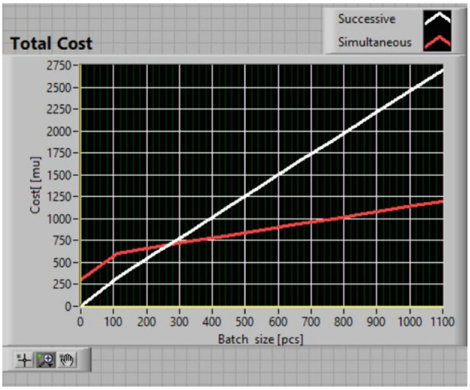

Fig. 2. The graphical representation of the functions Cost = f(BS)

4.2 Analytical Method

According to this method, the expressions that calculate the total cost for each machining way are equalled. All the variables involved have certain values for each process, except the batch size, which is unknown, and must be determined as the solution of the equation so formed. For a reasonable comparison of the two methods, they must be characterized by the same values of certain inputs (mainly those that describe the drills: quality, dimensions, and price). The number of holes processed at a time is one for successive machining, while for simultaneous is according to the technology. The main difference between the two is that the price of the multi-spindle head is zero at successive machining.

Replacing Eqs. (7), (8), and (9) in Eq. (10), and separating the variable BS (batch size) associating different indexes to the variables bound to each machining method, is obtained Eq. (11). The indexes 1 and 2 are associated to successive, and respectively to simultaneous machining. BS so calculated is the number of parts in the batch for which the two methods are equally expensive.

$$BS = Pd_2 + p * (ND_2 - ND_1) / (NP * Cmm * (Tb_1 / ngs_1 - Tb_2 / ngs_2)) \quad (11)$$

All these can be done either by means of a computer program, or in an Excel worksheet.

5 Case Studies

Several possible approaches are considered for the same part, presented in Fig. 3. It is a part of an electrical engine and made of aluminium. It has four parallel holes, geometrical identic. For data protecting purpose, no other dimensions or data are provided. It is to be determined the price of the consumed hardware and the total time to manufacture a certain batch in the two ways to machine the holes.

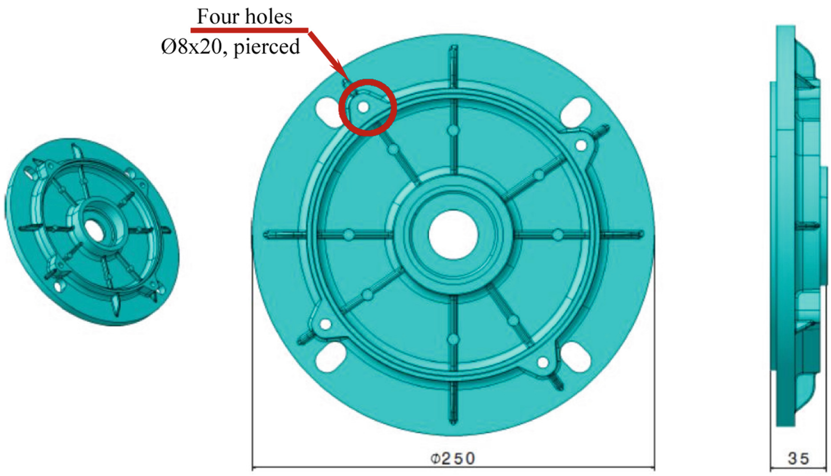

Fig. 3. The part having four parallel and geometric identical holes

5.1 Case Study #1

The data of case study are presented in parallel tables. The only difference between the two variants is using or not multi-spindle head to machine simultaneously the four holes on a part. For an easier interpretation of the data corresponding to the two ways of machining the holes, they are presented table shaped (Table 1).

It is easy to observe that the differences, for this simplest case are minimal: the number of drills needed is 4 times bigger, the hardware expenses 4.5 bigger, and total time 4 times shorter for the simultaneous drilling compared to successive drilling. This case study pointed to a very big batch size. Despite it requires more expensive hardware, because the simultaneous machining is a time saving process, it's total cost to manufacture the entire batch is about four times smaller than that of successive machining.

5.2 Case Study #2

This case study aims to emphasise that the batch size is very important when it comes to the costs of hardware. For this case study are presented only the data that differ from a kind of machining to the other one (Table 2).

In this case, the unbalance between the savings in terms of time and costs is much bigger. If using the same type of drills in the two machining ways, the batch size is important in relation to the capacity of work of a drill. If all the batch can be manufactured with a single drill, the simultaneous machining pays its effectiveness with an extra-consumption of three drills. If, on the other hand, manufacturing the entire batch needs four drills successively, this manner of working is weak both in terms of drill consumption, and effectiveness – drilling simultaneous will need, as well, four drills. As can be seen in Fig. 2, which displays the graphs drawn using the input data from the table above, for a batch size bigger than 250 pcs (roughly), the simultaneous machining becomes cheaper than the successive one. Under the mentioned value batch size,

Table 1. Comparison between successive and simultaneous drilling for case study #1

Successive drilling			**Simultaneous drilling**		
Variable	Symbol [lMU]	Value	Variable	Symbol [lMU]	Value
Price of multi-spindle head	Pd [lmu]	0	Price of multi-spindle head	Pd [lmu]	500
Price of the drill	p [lmu]	20	Price of the drill	p [lmu]	20
Diameter of the drill	d [mm]	8	Diameter of the drill	d [mm]	8
Tool-life	T [min]	15	Tool-life	T [min]	15
Length of the aTCive side of the drill	L1 [mm]	100	Length of the aTCive side of the drill	L1 [mm]	100
Remaining length of the drill at the end of total tool-life	L2 [mm]	30	Remaining length of the drill at the end of total tool-life	L2 [mm]	30
Length of the drill removed when re-sharpening	L3 [mm]	1	Length of the drill removed when re-sharpening	L3 [mm]	1
Hole length	L4 {mm]	20	Hole length	L4 [mm]	20
Useful length of the drill	L5 mm]	69	Useful length of the drill	L5[mm]	69
Batch size	Bs [pcs]	200000	Batch size	BS [pcs]	200000
Number of holes on a part	ng [pcs]	4	Number of holes on a part	ng [pcs]	4
Number of holes machined at a time	ngs [pcs]	1	Number of holes machined at a time	ngs [pcs]	4
Cutting speed	v[m/min]	40	Cutting speed	v[m/min]	40
Spindle speed	n [min^{-1}]	1592.36	Spindle speed	n [min^{-1}]	1592.36
Feed-rate	S [mm/rev]	0.20	Feed-rate	s [mm/rev]	0.20
Time to machine a hole	tb [min]	0.07	Time to machine a hole	tb [min]	0.07
The number of re-sharpenings	Nr [pcs]	69.00	The number of re-sharpenings	Nr [pcs]	69.00

(*continued*)

Table 1. (*continued*)

Successive drilling			**Simultaneous drilling**		
Variable	Symbol [lMU]	Value	Variable	Symbol [lMU]	Value
Total number of holes machined by a drill	Gd [pcs]	15696	Total number of holes machined by a drill	Gd [pcs]	15696
Necessary number of drills	ND [pcs]	51	Necessary number of drills	ND [pcs]	204
Total hardware expenses	TC [mu]	1020	Total hardware expenses	TC [mu]	4580
Total machining time	Tt [min]	52752	Total machining time	Tt [min]	13188
Expenses to use a machine-tool for one minute	Cmm [mu/min]	10	Expenses to use a machine-tool for one minute	Cmm [mu/min]	10
The total cost of machining the holes	Cost	528540	The total cost of machining the holes	Cost	136460

the simultaneous machining is more expensive (per part) because the cost of the multi-spindle head is shared to a low number of parts. As a general rule, it can be stated that the bigger is the batch size, the more cost saving is the simultaneous machining. If apply the Eq. (11) to the same set of input data, the solution is 237.41. This is the theoretical value, for whichever way to machine the holes is applied, the total costs for machining the holes are the same. Bellow this value, the successive machining is better, and above it, simultaneous machining is preferable in terms of costs.

5.3 Case Studies #3 and #4

These are the most complex case studies. They present in mirror the usage of different drills (same sized, but of different materials, and with different prices and technical performances. If the better drills (and more expensive, as well) are assigned to simultaneous drilling, the savings in terms of time are spectacular: the total time spent to manufacture the entire batch decreases more than 15 times. When the better drills are assigned to successive drilling, their higher performance is able just to balance the better effectiveness of simultaneous drilling – the two methods need the same time to finish the batch. Anyway, it can be stated that the higher technical performance of the drills (despite their bigger price) lead to better results both in terms of costs and effectiveness. If the weaker drills are used at simultaneous machining, they can waste all the advantages given by this way of working (Table 3).

Table 2. Comparison between successive and simultaneous drilling for case study #2

Successive drilling			**Simultaneous drilling**		
Variable	Symbol [lMU]	Value	Variable	Symbol [lMU]	Value
Price of multi-spindle head	Pd [mu]	0	Price of multi-spindle head	Pd [mu]	300
The price of the drill	p [mu]	60	The price of the drill	p [mu]	60
The batch size	BS [pcs]	1000	The batch size	BS [pcs]	1000
The number of holes machined at a time	ngs [pcs]	1	The number of holes machined at a time	ngs [pcs]	4
The necessary number of drills	ND [pcs]	1	The necessary number of drills	ND [pcs]	4
The total hardware expenses	TC [mu]	60	The total hardware expenses	TC [mu]	540
The total machining time	Tt [min]	263.76	The total machining time	Tt [min]	65.94
The total cost of machining the holes	Cost	2697.6	The total cost of machining the holes	Cost	1199.4

6 Discussions

Regardless the data which describe the batch and the drills, the simultaneous drilling must pay the cost of the multi-spindle head (Table 4). Since this is a constant, not depending on the batch size, the bigger the batch is, the bigger the savings of time, if drilling simultaneously. If the cost of hardware is the main criterion to appreciate the two methods, it is to be noted that the savings given by spending less drills, and no need for a multi-spindle head at successive drilling, are balanced by other supplementary costs: more handling of the parts and more personnel costs. This is clearly proved when it comes to talk in terms of total costs, as can be seen in the case studies. Also, the precision of the relative position of the holes might be affected by the successive machining. In these conditions, despite the higher expenses, the simultaneous drilling brings usually bigger general benefits than the successive one, mainly for the big batch size.

Table 3. Comparison between successive and simultaneous drilling for case study #3

Successive drilling			**Simultaneous drilling**		
Variable	Symbol [lMU]	Value	Variable	Symbol [lMU]	Value
Price of multi-spindle head	Pd [lmu]	0	Price of multi-spindle head	Pd [lmu]	500
The price of the drill	p [lmu]	20	The price of the drill	p [lmu]	80
The batch size	BS [pcs]	20000	The batch size	BS [pcs]	20000
The number of holes machined at a time	ngs [pcs]	1	The number of holes machined at a time	ngs [pcs]	4
Cutting speed	v [m/min]	40	Cutting speed	v [m/min]	80
Spindle speed	n [min^{-1}]	1592.36	Spindle speed	[min-1]	3184.71
The feed-rate	s [mm/rev]	0.20	The feed-rate	s [mm/rev]	0.40
Time to machine a hole	tb [min]	0.0659	Time to machine a hole	tb [min]	0.0165
The total number of holes machined by a drill	Gd [pcs]	15696	The total number of holes machined by a drill	Gd [pcs]	104641
The necessary number of drills	ND [pcs]	6	The necessary number of drills	ND [pcs]	4
The total hardware expenses	TC [mu]	120	The total hardware expenses	TC [mu]	820
The total machining time	Tt [min]	5275.2	The total machining time	Tt [min]	329.7
Expenses to use a machine-tool for one minute	Cmm [mu/min]	10	Expenses to use a machine-tool for one minute	Cmm [mu/min]	10
The total cost of machining the holes	Cost	528730	The total cost of machining the holes	Cost	41180

Table 4. Comparison between successive and simultaneous drilling for case study #4

Successive drilling			**Simultaneous drilling**		
Variable	Symbol [lMU]	Value	Variable	Symbol [lMU]	Value
Price of multi-spindle head	Pd [mu]	0	Price of multi-spindle head	Pd [mu]	500
The price of the drill	p [mu]	80	The price of the drill	p [mu]	20
Tool-life	T [min]	25	Tool-life	T [min]	15
The batch size	BS [pcs]	20000	The batch size	BS [pcs]	20000
The number of holes machined at a time	ngs [pcs]	1	The number of holes machined at a time	ngs [pcs]	4
Cutting speed	v[m/min]	80	Cutting speed	v [m/min]	40
Spindle speed	n [min^{-1}]	3184.7	Spindle speed	n [min-1]	1592.36
The feed-rate	s [mm/rev]	0.40	The feed-rate	s [mm/rev]	0.20
Time to machine a hole	tb [min]	0.0165	Time to machine a hole	tb [min]	0.0659
The total number of holes machined by a drill	Gd [pcs]	104641	The total number of holes machined by a drill	Gb [pcs]	15696
The necessary number of drills	ND [pcs]	1	The necessary number of drills	ND [pcs]	24
The total hardware expenses	TC [mu]	80	The total hardware expenses	TC [mu]	980
The total machining time	Tt [min]	1318.8	The total machining time	Tt [min]	1318.8
The total cost of machining the holes	Cost	13268	The total cost of machining the holes	Cost	14168

7 Conclusion

The output of the present work allows the user to make an argued decision when it comes to choose between simultaneous and successive drilling. The software tools provided, an Excel worksheet, and a computer program, allow the user to perform a detailed study of the implications of the different input data on the result, both in terms of costs, and effectiveness. Of course, the manufacturing engineer is the one able to interpret the output of the software tool in making the final decision, taking into account the advantages and drawbacks of each method and considering correctly all the input data.

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