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Comprehensive analysis and study of the machinability of a high strength aluminum alloy (EN AW-AlZn5.5MgCu) in the high-feed milling

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A B S T R A C T

This article is focused on studying and analysing the efficiency of the machinability of a high strength aluminium alloy (EN AW-AlZn5.5MgCu) in the high feed milling. The introduction of the article provides a brief description of high feed milling technology and presents best known research regards to the subject. The research of the time efficiency and economic efficiency of high feed milling of aluminium alloys consists of realization of two groups of experiments. The first group consists of four experiments carried out by progressive technology of high feed milling, and the second group contains one experiment conducted using conventional milling technology. The assessment of efficiency consists in determining the overall time and economic efficiency and also in comparison to the machining of aluminium alloys by high feed milling technology with conventional machining technology. The best results were obtained when the machining parameters were: cutting speed of 550 m/min, travel speed of 10600 mm/min, and feed per tooth of 0.85 mm. The material was removed in the contour roughing phase with a 42 mm plunge-cutting router. Using this cutter, it is possible to produce 19 pieces of components in a hour, which is more than half of the specified requirement. The production of components under the conditions and with this type of high feed milling cutter is more than 75 % shorter than production by a conventional method.

A R T I C L E I N F O

Keywords:
High-feed milling;
High strength aluminum alloy (EN AW-AlZn5.5MgCu);
Machinability; Efficiency;
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1. Introduction

Comprehensive simulation, exploration and analysis of the efficiency of the production process using high feed milling as a part of the major targets of the workload of current scientific practice. High feed machining determines the overall machining efficiency as the feed rate is equal to multiplying the feed by speed. Examining machinability, optimizing cutting parameters and all the influencing parameters, is immensely important to the efficient economic and cost-effective adjustment of the production process [1-3]. Competition in the global market in cutting operations is increasing from one hour to the next. Technologies, methods and processes to produce more efficiently and cheaper are daily innovated. A fundamental principle of each company is to achieve the minimum production time in connection with the minimization of production costs, thus ensuring an efficient production process. One of the trends that is in the forefront of small and medium enterprises in cutting operations all over the world is high feed machining [4-5].

High Feed Machining (HFM) is a method incorporated into progressive machining methods. It is three times faster than a conventional machining method. This technology has several advantages and disadvantages which are presented in Table 1. Using a suitable tool with this method, small depths of cut are allowed in conjunction with a high feed per tooth. The result of this machining process is a large amount of material removal. During high feed machining, the depth of cut is small, but the width of cut is optional with respect to the geometry of the tool [6].

The study of high feed machining is currently being dealt with by several experts around the world. For example, in the work of Ji *et al.* [8], the authors present the experimental findings of milling of titanium alloy TC11 using polycrystalline diamond (PCD) cutting tool at high feed rate. Authors Petru *et al.* [9] provide the evaluation of microstructure and microhardness of surface layer after high feed milling in their research. Mihail [10] publishes the research about the manner in which is running the high feed milling process in an orthogonal path pocket milling. The experimental modality follows the robust engineering approach, by the Taguchi Method. In 2015, authors Mwinuka and Mgwatu [11] present study about the tool selection for rough and finish CNC milling operations based on tool-path generation and machining optimisation. In 2015, author Choi [12] describes the influence of feed rate on the fatigue performance. The results demonstrate that a higher feed rate induces more compressive residual stresses and the effect of feed rate increases significantly if the loading is reduced. In 2016, Virginija Gyliene and Valdas Eidukynas present the research study of cutting forces assuming the geometry of the milling cutter in the field of high feed face milling [13]. In 2017, authors Zauskova *et al.* [14] describe the method of triaxial measurement of residual stress after machining the surface of sample by high feed milling technology. They compare the various methods of residual stress analysis after high feed milling. There are not so much studies about the high feed machining of aluminum alloys. In this article there is described the experiments for provision of efficient machining of aluminum alloys with high feed rate.

Table 1 Advantages and disadvantages of HFM technology

Advantages	Disadvantages
• Without high revolution of spindle requirements • Axial direction of cutting forces to the spindle • Reduction of vibration • Increased lifetime of tool and superior cut • It is possible to achieve up to 10 times the feed rate compared to the conventional machining method • Achieving of clean shapes that do not require semi - machining	• It is not possible to apply this method in older machines • Increased risk of vibration commencement • Increased noise level and formation of noise tone component during the cutting process • Fixed clamping of workpiece

2. Materials and methods

One of the appropriate ways to assess the production process is to evaluate its effectiveness. In general, the efficiency of machining is most easily defined by mathematical formulations [15] resulting in quantitative indicators that can subsequently be verified or optimized. The overall efficiency of machining by milling technology was determined by the basic time and cost-effectiveness of machining. Total time efficiency of machining is mathematically formulated as follows:

$$t_{total} = t_{load} + \frac{t_{mach}}{f_{mach}} + \frac{t_{ct}}{N} \tag{1}$$

where t_{total} is total machining time (s), t_{load} is the time taken to load and unload the part to and from machine tool (s), t_{mach} is actual machining time (s), f_{mach} is fraction of the time spent in removing material (s), t_{ct} is tool change time (s), and N is number of parts (-).

$$t_{mach} = \frac{V_{vol}}{f dV} \tag{2}$$

$$N = \frac{fdC^{1/n}}{V_{vol}V^{(1-n)/n}} \tag{3}$$

From this basic mathematical formulation of general time efficiency, the time efficiency for milling was derived in the following form:

$$t_{total} = t_{load} + \frac{1}{f_{mach}} \frac{V_{vol}}{\alpha n_c f dV} + \frac{V_{vol}V^{(1-n)/n}}{n_c f dC^{1/n}} t_{ct} \tag{4}$$

where α is rake angle (°), n_c is number of cutting edges (-), f_d is area of cut (mm^2), f_{dV} is volume removal rate (mm^3), V_{vol} is volume of material to be removed by milling [mm^3], C is Taylor coefficient (-), and V is linear cutting speed (m/s).

For the overall economic efficiency of machining in general, the following mathematical formula applies:

$$C_p = (M_t + M_w)t_{total} + \frac{V_{vol}V^{(1-n)/n}}{fdC^{1/n}} C_t \tag{5}$$

where C_p is the cost of manufacture (€), M_t is the charge rate (€), M_w is the labour charge rate (€), and C_t is the cost of consuming cutting edges (€).

From this basic mathematical formulation of general economic efficiency, the economic efficiency for milling was subsequently derived in the following form:

$$C_p = (M_t + M_w)t_{total} + \frac{V_{vol}V^{(1-n)/n}}{n_c f dC^{1/n}} C_t \tag{6}$$

$$M_t = \frac{C_i}{120000 f_0 n_s} \left[\frac{1}{Y} + (f_i + f_m\right] \tag{7}$$

where C_i is the initial purchase price (€), f_0 is fraction of n_s 8-hour shifts a day (n = 1, 2 or 3), 250 day in year, Y is number of years (-), f_i is fraction of the purchase price, and f_m is typically rises as the inflation rate of an economy increases.

High strength aluminum alloy (EN AW-AlZn5.5MgCu) was used to carry out the experiments. This alloy is composed of aluminum, zinc, magnesium and copper, the zinc being the alloying element. This alloy has excellent machinability; its surface is hard and is therefore suitable for etching of structures. It is also characterized by excellent surface polishability. The high strength aluminum alloy is mainly used for production of foam moulds, blow moulds, machine parts, press and cutting tools. The mass fraction of the alloying elements of the alloy is shown in the Table 2.

Five types of milling tools were used in the experiments, the characteristics of which are given in the Table 3. The pictures of individual tools are presented in the Fig. 1.

Table 2 The mass fraction of the alloying elements of the alloy EN AW ALZn5.5MgCu

Alloy	Alloying elements – mass fraction (%)								
	Fe	Si	Cu	Mg	Mn	Cr	Ti	Zn	other
EN AW ALZn5,5MgCu T651	0.50	0.40	1.20 2.00	2.10 2.90	0.30	0.18 0.28	0.20	5.10 6.10	0.15

Table 3 Technical specification of using tools

Tools	Diameter (mm)	No. of teeth (mm)	Max. cutting depth (mm)
Milling head	40	4	9
Face cutter	40	4	9
Plunge-cutting Φ42	42	3	15
Plunge-cutting Φ32	32	3	15
High feed milling cutter	20	4	1.15
Monolith cutter	12	4	1.5

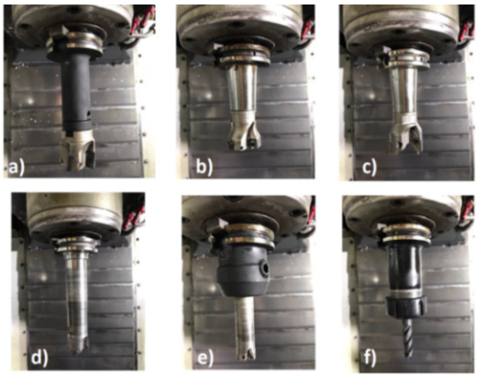

Fig. 1 Used tools: (a) Milling head, (b) Face cutter, (c) Plunge-cutting Φ42, (d) Plunge-cutting Φ32, (e) High feed milling cutter, (f) Monolith cutter

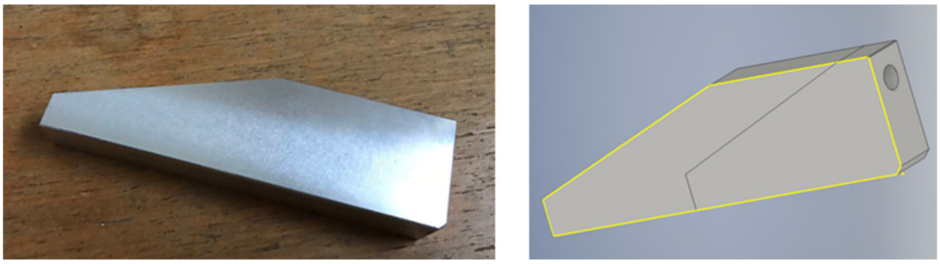

Fig. 2 Produced component (left) and built 3D model (right) – EN AW-AlZn5.5MgCu

During the experiments aimed at analysing the efficiency of high feed machining of aluminum alloys, the simulation method was used. Through this method and the 3D CAD program a basic machining program was created. This program was subsequently imported into the CNC machining centre, which was used for machining of a 115 × 35 × 20 mm blank. The display of the produced component is shown in the Fig. 2.

3. Description of the experiments conducted

To ensure the reliability of the results achieved, five basic experiments were carried out:

- The experiment No. 1– using the face milling cutter
- The experiment No. 2 – using the plunge – cutting cutter Φ42
- The experiment No. 3 – using the plunge – cutting cutter Φ32
- The experiment No. 4 – using the high feed milling cutter
- The experiment No. 5 – machining by conventional milling technology

In all experiments, in addition to the above, a milling head and a monolith cutter were used. In the first four experiments, it is about a progressive high feed milling technology. The experiment No. 5 is about machining with conventional milling technology, which serves for subsequent comparison of high feed milling with conventional milling. As the high feed milling is performed in the first four experiments, the feed rate values should be above 2,000 mm/min and the depths of cut should not exceed 2 mm. An example of clamping of the blank during the experiment is illustrated in the Fig. 3.

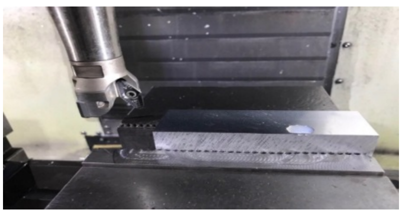

Fig. 3 Experimental realization – clamping of the blank

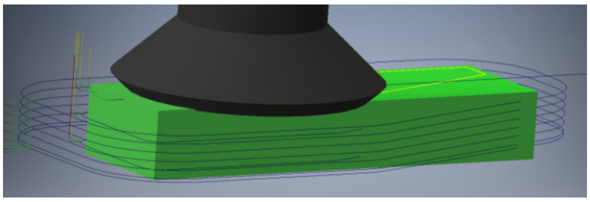

Fig. 4 Simulation of the head alignment of the produced component

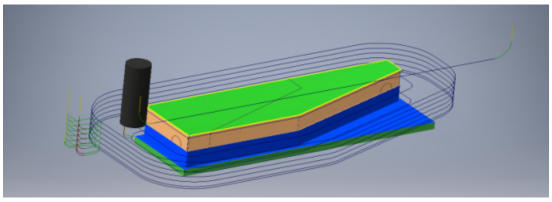

Fig. 5 Simulation of contour milling of the produced component

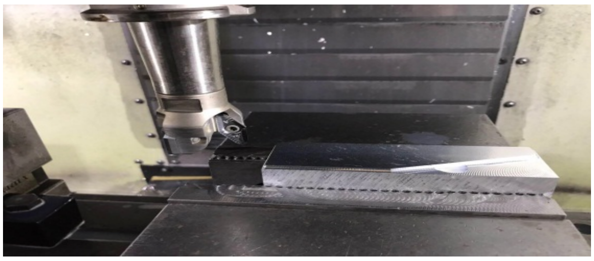

Fig. 6 Experimental realization – contour milling

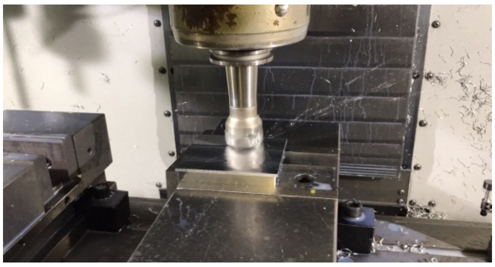

Fig. 7 Experimental realization (second clamping) – head machining

The component was produced in two clampings. During the first clamping, the head was aligned and the simulation is captured in the Fig. 4. The head was aligned using the 40 mm diameter milling head with 4 teeth. Alignment of the head with a total thickness of material removal of 0.5 mm was performed during all five experiments.

After aligning the head, the contour milling, i.e. the circumference of the produced component (Fig. 5), was realized. Contour milling was performed in accordance with a pre-assembled simulation of the tool movement and the required thickness of the material removal (Fig. 6). In this operation, milling cutters of different types and diameters were used according to the specific order of the experiment.

In Fig. 7, the second clamping is different for the processes of the progressive and conventional milling method. In the processes in which the high feed milling method (experiments 1-4) is used, the second clamping is composed of two operations – roughing of the head and deburring to the required thickness and surface quality. In conventional milling, only one operation is performed in the second clamping – roughing of the head to the desired dimension with a gradual removal of 1 mm thick material.

During the experiments, individual cutting conditions were calculated for specific tools, the chosen machine and material. The calculated cutting conditions can be divided into three basic areas. The cutting conditions, that were set for all experiments in the head roughing and material removal operations to achieve the required quality are the first area. The particular values of the cutting parameters and the identification of the tools used are given in the Table 4.

Cutting parameters in the second area are determined individually for each experiment in contour roughing operations (experiments No. 1, No. 2, No. 3, No. 4). The individual values of the cutting parameters are given in Table 5.

Table 4 Cutting conditions for selected operations in all experiments

Operation / Parameter	Face roughing	Material reduction for achieving the required quality
Milling cutter	Milling head	Monolith cutter
Diameter (mm)	40	12
No. of teeth	4	4
Cutting speed (m/min)	180	120
Travel speed (mm/min)	480	768
Cutting depth (mm)	1.8	1.5
Speed (min^{-1})	1500	3200
Feed per tooth (mm)	0.08	0.06

Table 5 Cutting conditions for contour roughing: Experiment No. 1, No. 2, No. 3, No. 4

	Experiment No. 1	Experiment No. 2	Experiment No. 3	Experiment No. 4
Diameter (mm)	40	42	32	42
No. of teeth	4	3	3	3
Cutting speed (m/min)	200	550	500	550
Travel speed (mm/min)	3200	10600	2160	10600
Cutting depth (mm)	1	2	2	2
Speed (min^{-1})	4000	4100	6000	4100
Feed per tooth (mm)	0.2	0.85	0.12	0.85
Total depth of material reduction (mm)	15	15	15	15

The third area determines the conditions and cutting parameters for the experiment No. 5 – machining by conventional milling technology. When machining by conventional milling technology, other conditions were used than in previous experiments. The individual conditions in specific operations are found in the Table 6 and Table 7. The cutting conditions for the first clamping are shown in the Table 6 and the cutting conditions for the second clamping are given in the Table 7.

Table 6 Cutting conditions, experiment No. 5 – the first clamping

	Face alignment	2×contour roughing	Material reduction for achieving the required quality
Milling cutter	Milling head	Monolith cutter	Monolith cutter
Diameter (mm)	40	12	12
No. of teeth	4	4	4
Cutting speed (m/min)	120	120	120
Travel speed (mm/min)	230	768	768
Cutting depth (mm)	1.5	1.5	1.5
Speed (min^{-1})	1000	3200	3200
Feed per tooth (mm)	0.08	0.06	0.06

Table 7 Cutting conditions, experiment No. 5 – the second clamping

Operation	Roughing of face milling
Milling cutter	Milling head
Diameter (mm)	40
No. of teeth	4
Cutting speed (m/min)	120
Travel speed (mm/min)	230
Cutting depth (mm)	1
Speed (min^{-1})	1000
Feed per tooth (mm)	0.08

4. Results and discussion

The experiments performed were evaluated in terms of overall time and economic efficiency. To evaluate overall efficiency, the material used, machining technology and overall manufacturing system management must be taken into account. Evaluation of the overall efficiency is based mainly on Eqs. 4 and 6.

In order to meet the stated objective which is assessing the overall time efficiency of aluminum alloy machining, the basic machining time for one piece of manufactured component was determined in individual experiments, as shown in the Table 8 and Fig. 8.

Table 8 Machining time for one piece of manufactured component

No. of experiment	Time τ_s (min)
1	3.47
2	1.51
3	1.54
4	4.24
5	10.71

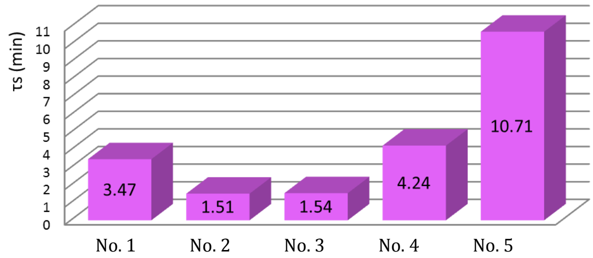

Fig. 8 Graphical interpretation of machining time for one component

Table 9 Total production time of experiments for one piece of manufactured component

No. of Experiment	Total production time (min)
1	4.97
2	3.01
3	3.04
4	5.74
5	12.21

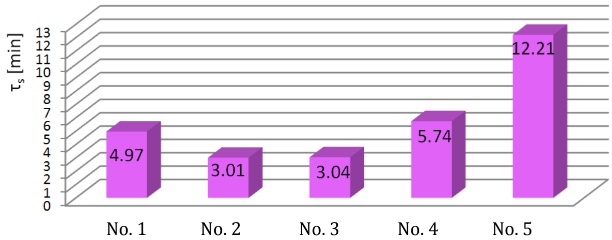

Fig. 9 Graphical interpretation of total production time of individual experiments in the production of one component

From the results of the machining time for one component it can be stated that the best choice from the viewpoint of minimizing the net production time is the second experiment using high-feed milling during which the component was produced (net machining time) in 1.51 min. The worst machining time was achieved by conventional milling method (experiment No. 5).

The overall assessment of the time effectiveness of individual experiments consists of an assessment of the total production time of one component presented in the Table 9 and Fig. 9 and batch production. Comparison of the machining results obtained using high feed milling and conventional milling is also included in the overall assessment of the time-effectiveness of the individual experiments.

As seen in the previous chart and summary table, the most appropriate experiment in the production of one component is the experiment No. 2 – high speed milling, in which a 42 mm plunge-cutting router was used at cutting speed of 550 m/min.

For a more adequate assessment of the manufacturing process, the production time for a single batch production of 1 200 pieces was set. The results of the production time are interpreted in the Table 10 and Fig. 10.

The graphical interpretation of total production time for the batch production in individual experiments confirmed the results achieved for one piece of the manufactured component. As seen in the assessment of the production time of the batch production that is equal to 1200 pieces, the best use of the tools and cutting conditions is described in the experiment No. 2.

Table 10 Total production time of experiments – production batch

No. of experiment	Production time – one batch (min)
1	5964
2	3612
3	3648
4	6888
5	14652

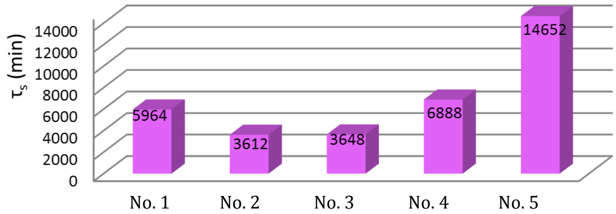

Fig. 10 Graphical interpretation of total production time for experiments – production batch

In order to achieve complete results in the study of the time efficiency of machining of aluminum alloys, an evaluation of conventional milling with realized experiments No. 1-4, in which the high feed milling method was applied, was subsequently implemented. The assessment is carried out by determining the difference among the individual experiments of high speed and conventional milling, as well as the percentage.

The evaluation presented in Table 11 shows that each of the experiments using high feed milling technology is at least two times more time efficient than experiments using the conventional milling method of the component.

Table 11 Comparison of experiment results conducted by HFC method and conventional milling

	HFC method – Experiment No. 1	HFC method – Experiment No. 2	HFC method – Experiment No. 3	HFC method – Experiment No. 4
τs (min) – one piece – HFC methods	4.97	3.01	3.04	5.74
τs (min) – one piece – Conventional milling (Experiment No. 5)	12.21	12.21	12.21	12.21
Time difference	7.24	9.2	9.17	6.47
Percentage	59.296	75.348	75.102	52.989

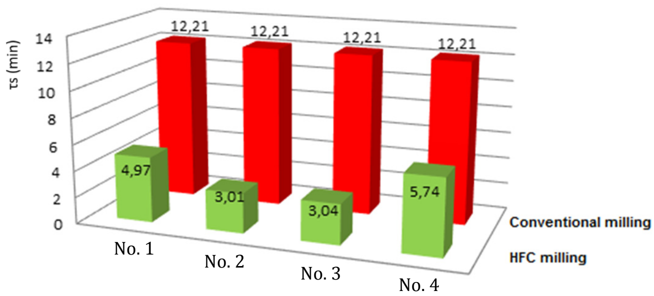

Fig. 11 Graphical comparison of experiments conducted by HFC method and conventional milling

As shown in Fig. 11, after an overall assessment of the time efficiency, it can be stated that of all experiments considered, in order to produce the product in the shortest possible time, it is best to choose high feed milling – namely the parameters specified in the experiment No. 2 which is 75.348 % more time efficient than conventional milling of the material.

The parts of Eqs. 6 and 7 were used to assess the economic efficiency of high feed machining of aluminum alloys. Determination of investment costs for roughing operations is presented in the Table 12.

The price of plates when using a 42 mm plunge-cutting router, which was used in the most time efficient experiment (experiment No. 2), is because the cutting inserts used are made of the material that is the most suitable for machining of aluminum and its alloys. This tool in combination with the given cutting inserts has the longest lifetime for the given parameters, approximately 6000 hours.

To ensure the economic process, it is necessary to choose the tool with the highest life expectancy to delay the additional investment costs of purchasing the tools. Due to the fact that the lifetime of the other tools used is around 3000 hours, the use of alternative No. 2 is considered to be the most appropriate.

Table 12 Determination of investment costs for roughing operations

	No. of plate	Price of tool (€)	Unit price of plate (€)	Price for all plates (€)	Total price of tool with plates (€)
Face milling Φ40	4	380	7	28	408
Plunge-cutting Φ42	3	400	12	36	436
Plunge-cutting Φ32	3	360	8	24	384
High feed milling cutter Φ20	4	160	6.5	26	186

Table 13 Determination the number of pieces produced per hour

No. of experiment	Total production time – one piece of component (min)	No. of pieces produced per hour
1	4.97	12.07
2	3.01	19.93
3	3.04	19.74
4	5.74	10.45
5	12.21	4.91

The value of the produced component is € 2.5 without the material used. Given the fact that in practice the overhead costs are € 20, it is necessary to produce at least 8 pieces in 1 hour to guarantee the efficiency and profitability of the production process. On the basis of the previous determination of time efficiency, it is possible to determine the number of pieces produced per hour in individual experiments. This determination is presented in the Table 13.

According to the criteria set and financial options, it was necessary to produce at least eight pieces of components in one hour to ensure the profitability of the production process. According to the above calculations, the second alternative (the HFC machining method) was confirmed as the most appropriate option in terms of economic efficiency of production.

The graph in the Fig. 12 shows the results obtained from the previous table, with the red line marking a minimum requirement for the number of pieces to be manufactured to ensure the profitability and economic efficiency of the production process.

Based on the evaluation of the economic efficiency of individual experiments, the parameters used in the experiment No. 2 can be considered as the most appropriate solution. This proposal is the best suited both economically and in terms of time efficiency.

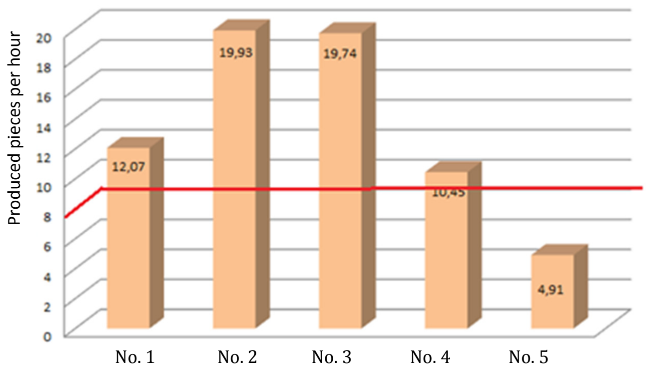

Fig. 12 Graphical interpretation of produced pieces per hour

5. Conclusion

Aluminium alloys are among the primary materials used in the transport industry, mainly in the automotive and aircraft industry [16-18]. Applied research oriented to solving partial problems in manufacturing processes of mass production to which the transport industry undoubtedly belongs, it is currently dealing with time efficiency of production [19-21]. Reducing production time has a direct impact on the total cost of production [22-23]. The high feed machining method undoubtedly ranks into the progressive machining technologies, the use of which the aforementioned factors can be achieved. They were observed the key factors such as time efficiency, reduction of production time, total cost of production, cost reduction, economic efficiency and cost-effectiveness. The results obtained show that the production process is most efficient when using a 42 mm plunge-cutting router in the contour roughing phase in terms of both time and economy. Using this milling cutter, it is possible to produce 19 pieces in one hour, which is more than half of the number required. The production of components under the conditions using this type of high-feed milling cutter is more than 75 % shorter than production by a conventional method. In conclusion, although the machining of aluminum and aluminum alloy materials by means of high feed milling technology is more costly in terms of investment costs, this slightly negative property is sufficiently balanced in terms of time efficiency and productivity. The research carried out in the presented article points out that the machining by the progressive high feed milling method is a suitable option for smaller companies that need to achieve a faster production of components of the required quality at an affordable price.

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