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IMPROVEMENT OF THE GEAR TOOTH MILLING PROCESS: A CASE STUDY IN A SMALL COMPANY

MELHORIA DO PROCESSO DE FRESAMENTO DE DENTES DE ENGRENAGEM: ESTUDO DE CASO EM UMA PEQUENA EMPRESA

MEJORA DEL PROCESO DE FRESADO DE DIENTES DE ENGRANAJES: UN ESTUDIO DE CASO EN UNA PEQUEÑA EMPRESA

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ABSTRACT

The increase in competitiveness and the pursuit of efficiency lead companies to optimize their production processes, including machining, which is widely used in the industry. This study focused on improving the gear milling process in a small company with the aim of increasing productivity. To achieve this goal, specific objectives were established, such as mapping the current process time, evaluating the tool's lifespan, conducting practical tests with a new tool proposal, and analyzing the results. The study was based on a literature review on machining process improvements and cutting tools, and a case study using machining strategies, time mapping, and tool lifespan before and after implementing improvement measures. The test results demonstrated the effectiveness of the actions taken, such as increased production capacity and company efficiency, highlighting the proper selection of cutting tools and finding parameters as an important factor in ensuring the quality of the machining process. Continuing work on other machines in the company was suggested. This study demonstrated that optimizing the machining process can bring competitive improvements to companies.

RESUMO

O aumento da competitividade e a busca pela eficiência levam as empresas a otimizar seus processos de produção, incluindo a usinagem, que é amplamente utilizada na indústria. Este estudo focou na melhoria do processo de fresamento de dentes de engrenagem em uma pequena empresa com o objetivo de aumentar a produtividade. Para atingir esse objetivo, foram estabelecidos objetivos específicos, como mapear o tempo do processo atual, avaliar a vida útil da ferramenta utilizada, realizar testes práticos com uma nova proposta de ferramenta e analisar os resultados. O estudo foi baseado em uma pesquisa bibliográfica sobre melhorias no processo de usinagem e ferramentas de corte e estudo de caso utilizando estratégias de usinagem, mapeamento de tempos e vida útil da ferramenta antes e depois da implementação de medidas de melhoria. Os resultados de testes realizados demostraram a eficácia das ações realizadas, como aumento da capacidade produtiva e eficiência da empresa, destacando como fator importante a seleção adequada de ferramentas de corte e parâmetros de usinagem para garantir a qualidade do processo de usinagem. Foram sugeridas a continuação do trabalho em outras máquinas da empresa. Este estudo demonstrou que a otimização do processo de usinagem pode trazer melhorias competitivas para a empresas.

RESUMEN

El aumento de la competitividad y la búsqueda de eficiencia llevan a las empresas a optimizar sus procesos de producción, incluyendo el mecanizado, que es ampliamente utilizado en la industria. Este estudio se centró en mejorar el proceso de fresado de engranajes en una pequeña empresa con el objetivo de aumentar la productividad. Para lograr este objetivo, se establecieron objetivos específicos, como mapear el tiempo del proceso actual, evaluar la vida útil de la herramienta utilizada, realizar pruebas prácticas con una nueva propuesta de herramienta y analizar los resultados. El estudio se basó en una revisión bibliográfica sobre mejoras en el proceso de mecanizado y herramientas de corte, y un estudio de caso utilizando estrategias de mecanizado, mapeo de tiempos y vida útil de la herramienta antes y después de implementar medidas de mejora. Los resultados de las pruebas realizadas demostraron la eficacia de las acciones tomadas, como el aumento de la capacidad productiva y la eficiencia de la empresa, destacando la selección adecuada de herramientas de corte y parámetros de mecanizado como un factor importante para garantizar la calidad del proceso de mecanizado. Se sugirió continuar el trabajo en otras máquinas de la empresa. Este estudio demostró que la optimización del proceso de mecanizado puede traer mejoras competitivas para las empresas.

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1. INTRODUCTION

Due to the high competitiveness of the current market, it is necessary for managers to strategically align their processes from the beginning of their business activities (Costa et al., 2019). The industry is increasingly looking for innovation, whether in new products or in new and more efficient production methods. This reality reinforces the need to optimize time, improve quality and reduce production costs (Lafin, 2018).

Machining can be defined as a mechanical manufacturing process that uses cutting tools to remove material from a raw part and transform it into a finished part with desired dimensions, tolerances and surface finishes (Klocke, 2011).

Milling is a material removal machining process that aims to obtain different surfaces using various types of tools. The tool rotates around its own axis and the workpiece is clamped directly on the table or in a vise and moves along a Cartesian path. This is tangential milling or face milling, the two basic types most used in these machining processes (Ferraresi, 2018).

In the sector of machining services, the company becomes competitive when it performs its processes with quality, repeatability, speed and low cost. By adjusting and changing the process in pursuit of continuous improvement, waste is eliminated through research and development of new technologies (Silva, 2019).

The case study was motivated by the customer's need to outsource a large volume of parts, which required the company in question to increase its production capacity and efficiency to meet this demand.

The problem of this research stems from the fact that the machining of the part is performed on a machine where the machining parameters are predetermined depending on the tool. From this context the question is: What are the effects of optimizing the milling process of gear teeth, including the proper selection of cutting tools and machining parameters, on the productivity and efficiency and costs involved of a small company in the manufacture of gears?

The evaluation of the application of a more efficient machining method was carried out through a case study with a company in the sector called Alfa, which has existed for 16 years and operates in the provision of machining services for several industries. This study was based on a bibliographical research carried out through the Google Scholar platform, limited to the period from 2010 to 2022. It is important to highlight that advances in machining technology and in the development of new tools and techniques are a continuous and evolutionary process, and that this was a period when many of these advances began to consolidate and gain prominence in scientific research and industry, especially for high-speed machining (HSM) and new tool materials, such as ceramics. The search syntax was: "Machining process improvements" and "Cutting tools" and "Milling process performance".

The general objective established was to improve the process of milling gear teeth on a vertical machining center and increase productivity. From this main question, specific objectives arise:

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i. Map the current process time;
ii. Evaluate the useful life of the tool currently used;
iii. Carry out practical tests with another proposed cutting tool;
iv. Analyze the results obtained and compare with the current process.

The work was divided into four chapters. The second chapter brings a brief bibliographic overview on machining services, vertical machining center and machining processes. The third chapter presents the methodology used in the development of the work. In the fourth chapter, all analyses and presentations of tests carried out in a Computer Numerical Control (CNC) machining center are carried out, where machining strategies, mapping of machining times and tool life are explained before and after the publication of the parameters used and the implementation of relevant improvement measures. In the fifth chapter, the effective results of all the work are presented through data collected in the past and current state. In this way, the effectiveness of the action is verified and the objectives outlined for the work are achieved. After evaluating the results, conclusions and suggestions are presented for the continuation of the execution of the work for other machines in the work sector.

2. THEORETICAL BENCHMARK

This section presents a summary of the literature on the theory that addresses the main issues of the research problem. Therefore, this bibliographic review was based on citations of selected authors and publications relevant to the theoretical foundation of this work.

2.1 Machining Methods

Machining is a manufacturing process that involves removing material from a blank to produce a part of the desired shape, dimensions, and finish. It is performed with the help of cutting tools, such as drills, milling cutters, among others. The cutting tool is pressed against the surface of the raw piece, causing the material to be removed and shaping the piece (Machado et al., 2009).

Any machining process has two types of interrelated variables. These are the input (independent) and output (dependent) variables (El-Hofy, 2018).

A. Input variables (independent):

- Part material, such as composition and metallurgical features.
- Initial workpiece geometry, including previous processes.
- Selection of the process, which can be conventional or unconventional.
- Tool material.
- Machining parameters.
- Fixing devices.
- Cutting fluids.

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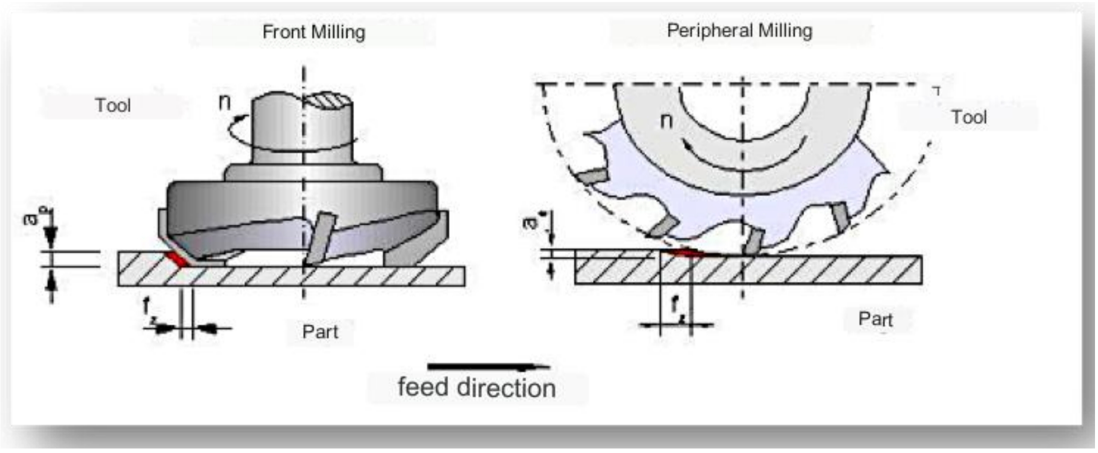
B. Output variables (dependent):

- Cutting strength and power.
- Influences deflection and vibration.
- Precision of the finished part.
- Heat generation and consequently tool wear.
- Geometry of the finished product.
- Desired mechanical properties.
- Surface finish.

Milling is a machining process that involves removing material from a workpiece through the rotary motion of a cutting tool called a milling cutter (Klocke, 2011). The milling process is applied with a tool performing rotational and translational movements shared between the workpiece and the tool (Stoeterau, 2004). Figure 1 shows the process for end and face milling.

Figure 1. Kinematics of the Milling process



Source: Stoeterau (2004)

It starts with clamping the part on a milling machine. The cutter is then mounted on the machine head and positioned so that its teeth are in contact with the workpiece surface. The milling machine is then turned on and the milling cutter begins to rotate at high speed while moving along a path defined by the machine's programming. There are different types of cutters such as end mills, profile cutters and gear cutters, each designed for a specific type of cut (Klocke, 2011).

This is a process that requires knowledge of geometry, material mechanics, fluid mechanics, among other areas. The proper selection of the cutting tool, machining parameters and lubrication directly influences the guarantee of the quality of the final product and machining efficiency (Machado et al., 2009).

The economics of the machining process are governed by cutting speed and other variables, as well as cost and economic factors. Machining economy represents an important aspect. Ecological aspects and health risks must be considered and eliminated by taking the necessary measures (El-Hofy, 2018).

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2.2 Center Vertical Machining

Aspects of the machine tool include various elements such as the structure, the drive system, the control system, the lubrication system and the cooling system. The machine tool is a complex piece of equipment that involves several aspects, from the structure to the lubrication and cooling systems. The proper choice of machine tools and the regular maintenance of these systems are essential to guarantee the quality and efficiency of the machining process (Diniz et al., 2014).

The development of machine tools is significantly driven by lower price and higher operational capacity of electronic devices, new types of drives, especially linear motors. This favoritism, combined with the market demand for machines capable of producing with the highest quality, in the shortest possible time and with maximum production flexibility, led to the development of machine tools that allow the production of parts with the greatest possible variety (Stoeterau , 2004).

The structure of the machine tool is responsible for supporting all dynamic and static loads that occur during the machining process. This structure must be rigid and stable to ensure the accuracy and quality of the final product. The drive system consists of electric or hydraulic motors that provide the necessary power to move the parts and tools during machining. These motors must be capable of providing a wide range of speeds and torques to meet different machining requirements (Diniz et al., 2014).

The vertical machining center is an extremely versatile machine tool designed for a wide range of machining applications from manufacturing environments to tool shops. In addition to geometric stability, precision, high performance and productivity, they offer high rigidity even during demanding machining operations.

The control system is responsible for managing all movements of the machine tool, such as the position and speed of the cutting tool and the part being machined. Modern control systems are highly sophisticated and use CNC technology, which allows programming and automating machining operations (Diniz et al., 2014).

The CNC vertical machining center (Figure 2) offers the operator the possibility of programming the cutting strategy of the desired part on a monitor attached to the machine or connecting to a specific programming software where the path of the tools selected for production will be generated. the piece itself.

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Figure 2. Romi Vertical Machining Center

Source: https://www.romi.com/produtos/linha-romi-d-nova-geracao/

2.3 Tools Cutting

Milling is a machining technique that uses a rotating cutting tool to remove material from a workpiece, creating a profile or cavity on its surface. The choice of cutter, cutting speed and feed rate are crucial for cutting quality and tool life (Klocke, 2011). In order to achieve goals and gain efficiency in companies, it is important to control operational performance in machines and equipment (Schnorrenberger & Nunes, 2019).

Improved machining is a risky challenge when cost and environmental impact must be considered. Tool life, material recycling, energy consumption, environmental pollution are direct and indirect factors that increase costs during various machining processes (Abdelrazek et al., 2020).

Cutting tools are classified according to the type of operation they perform, such as turning, milling, drilling, among others. Each type of tool is designed to perform a specific operation efficiently and precisely and are composed of several elements, such as substrate, coating, cutting angle, nose radius, cutting geometry, among others (Toenshoff & Denkena, 2013).

Vibrations during machining are an inevitable part of the process; they have a forced character and always accompany the cutting action inherent in the process in which the chip is created. In fact, cutting vibration is a detrimental factor that reduces performance and prevents better material removal strategies (ISCAR, 2022).

The cutting angle is the inclination of the tool face relative to the feed line. This angle directly affects the type and force of the cut and must be adjusted according to the material to be machined. The nose radius is the roundness of the tool's cutting edge. This radius reduces stress concentration on the cutting edge and improves machined surface quality. Cutting geometry is determined by the shape and position of the tool face in relation to the part being machined. This geometry must be chosen according to the characteristics of the material to be machined and the operation to be performed (Toenshoff & Denkena, 2013).

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The most common practice is to vary cutting parameters between speed and feed, which often results in reduced productivity. Therefore, any effective method of vibration reduction that does not harm the productivity of the operation will be the differential of continuous improvement (ISCAR, 2022).

Reducing friction during machining processes can also be achieved by improving the properties of the cutting tool. Coating the surface of the cutting tool by "physical vapor deposition" (PVD) or "chemical vapor deposition" (DCV) is one of the innovative techniques, where the surface of the cutting tool is coated with a micro-thick layer composed of a layer hard, anti-friction, chemically inert and thermally insulating (Abdelrazek et al., 2020).

The coating is applied over the substrate to protect the cutting tool from wear and oxidation. The most common coatings are TiN (titanium nitride), TiCN (titanium carbonitride) and TiAlN (titanium aluminum nitride). The substrate is the foundation of the tool and must be strong and rigid to withstand the high cutting forces. The most used materials for the substrate are high-speed steel, tungsten carbide, cermet and ceramic (Toenshoff & Denkena, 2013).

Therefore, cutting tools are fundamental elements in machining and must be designed and selected according to the characteristics of the material and the operation to be carried out. The proper choice of materials, coatings, cutting angles, nose radii and cutting geometries is essential to ensure the quality and efficiency of the machining process (Toenshoff & Denkena, 2013).

In this sense, when the choice of tool geometry is correct for your application, the cut is smooth and stable. Geometry strongly influences cutting force oscillations, chip evacuation and other factors directly related to vibration modes (ISCAR, 2022).

Solid carbide tools have cutting edges that separate the chips. A skillfully defined tooth pitch is an effective way to significantly improve the dynamic behavior of a cutting tool. ISCAR CHATTERFREE monolithic carbide cutters (Figure 3) are designed according to pitch control method. The cutter has different pitch angles combined with different helix angles. This concept guarantees vibration-free milling.

Figure 3. Carbide end mill with varied helix

Source: https://www.iscar.com/newarticles.aspx/lang/bz/newarticleid/4205

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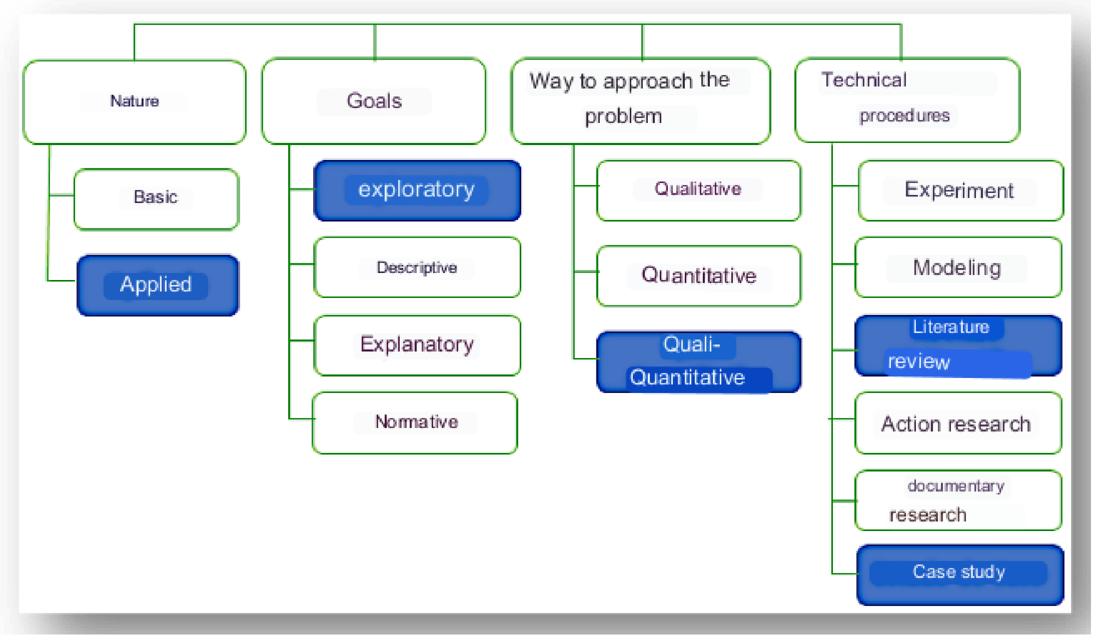
Cutting tools are essential elements in machining processes, as they ensure efficient removal of material from the part being machined, giving shape and finishing to the part.

3. METHODOLOGY

To carry out this work, the definition of the method, based on Gil (2002) and Knechtel (2014), is classified as applied, whose objectives are exploratory, with a qualitative and quantitative approach, and the technical procedures are bibliographical review to support the case study. The structure is described in the flowchart of Figure 4.

Figure 4. Work research method flowchart



Source: Adapted from Gil, 2002 and Knechtel, 2014.

The applied nature includes the availability of knowledge and the application of knowledge for economic and social benefit. It is characterized as exploratory because it provides greater familiarity with the problem, making it more explicit, leading to the construction of hypotheses (Gil, 2002). The problem-solving approach is a qualitative-quantitative research model that interprets quantitative information through numerical symbols and qualitative data through observation, participatory interaction and interpretation of the subjects' discourse (semantics) (Knechtel, 2014).

In the bibliographic search, already processed material was used, consisting mainly of scientific articles on themes and their questions related to the theme of this study. For this research, the Google Scholar platform limited to the period from 2010 to 2020 was selected and the keywords were “Improvements in the machining process” and “Cutting tools”.

Case studies, focusing on contemporary phenomena (Yin, 2015), is the technical procedure chosen in this work. In case studies, it is necessary to make observations and collect data, which is normally analyzed by this method. One approach to this technical procedure is to evaluate the practical application of the bibliographic research described above, for which the exploratory research is carried out in five stages:

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- Definition of the company with the occurrence of the experiment in the past;
- Identification of problems arising from the production process;
- Analysis of times generated during machining;
- Research and data collection on the strategies used;
- Detailed evaluation of the collected data and analysis of your conclusions about the object of this work.

Exploratory research and detailed observation of a company called Alfa was carried out. These allowed some conclusions about the object of this work. It is worth mentioning that this company has been operating for 16 years in the provision of machining services for various sectors: automotive, airport, agricultural among others.

The object of this case study is a small company that has a CNC machining center from the manufacturer Romi model D800 in its machining process, and that machines various types of parts. A part model called Turnstile was selected, which is supplied in the raw state manufactured by the casting process in Gray Cast Iron (Figure 5).

Figure 5. Raw cast turnstile

Source: Authors (2023)

The part is initially machined by the turning process and later fixed by the center directly supported on the table (Figure 6), to be machined the teeth by the milling process. The company did not authorize the reproduction of the technical drawing due to the confidential information contained therein.

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Figure 6. Ratchet attached to the machining center table

Source: Authors (2023)

It was verified in the current process, the use of a straight end mill, carbide, Ø10mm, 4 cuts, with coverage from supplier 1, as shown in Figure 7.

Figure 7. Cutting tool features

Source: Authors (2023)

Supplier 2 presented for testing the proposed tool EC-E4L 10-31/34C10CF72908, a 4-flute end mill, with different helix angles, variable pitch with high material removal rates, efficient chip evacuation, to roughing and finishing operations with the aim of improving machining performance (Figure 8).

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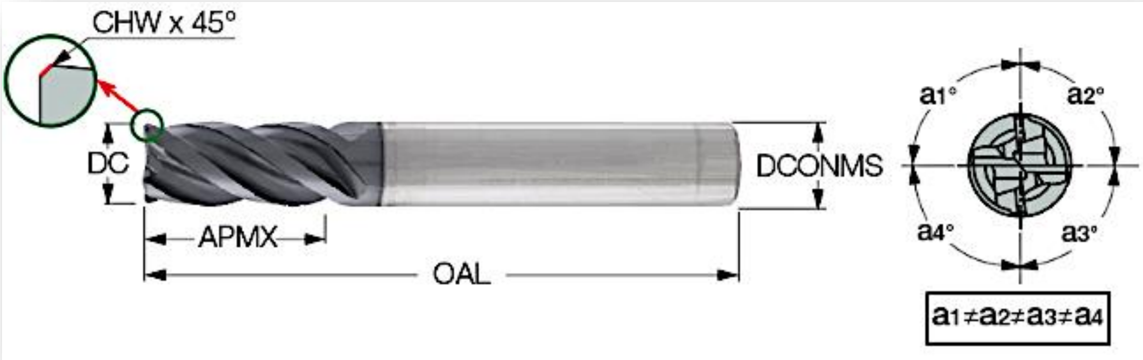
Figure 8. Characteristics of the EC-E4L 10-31/34C10CF72908 tool



Source: https://www.iscar.com/eCatalog/Family.aspx?fnum=3736&mapp=ML&app=0&GFSTYP=M

The machining strategy used was contour with constant Z (without retraction) and the machining parameters were adjusted according to the guidelines of suppliers 1 and 2 shown in Figure 9.

Figure 9. Machining parameters according to supplier guidelines

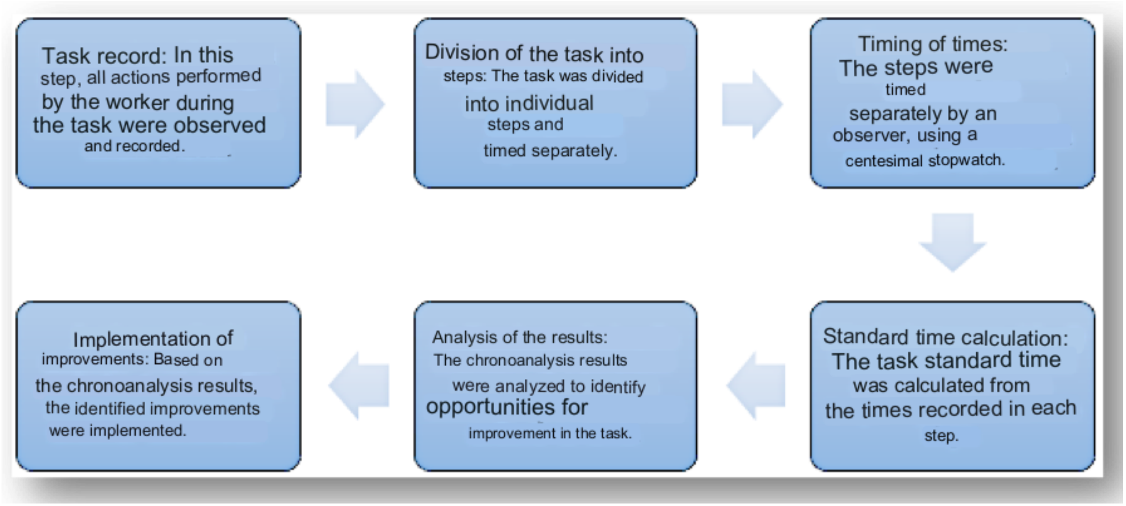
		Supplier 1	Supplier 2
Rotation (n)	rev./min.	6000	6000
Tool Diameter	mm	10	10
Number of teeth (z)	qtd	4	4
Cutting Speed (Vc)	m/min.	188	188
Knife Advance (fz)	mm/tooth	0.0667	0.05
Feed per revolution (1)	mm/rot.	0.2668	0.2
Table advance (Vf)	mm/min.	1601	1200
Machined length (1)	mm		
Depth of Cut (app)	mm	0.5	4
Cutting Width (ae)	mm	10	10
consumed power	kw		

Source: Authors (2023)

Chronoanalysis was applied for the case study, which according to Barnes (1968) is a method used to determine the standard execution time of a machining operation. It is based on observation and analysis of the time spent by a skilled operator to perform a given operation.

The author defines chronoanalysis as "the process of recording, measuring and analyzing the time required to perform a specific task or operation, with the purpose of establishing a time pattern and identifying opportunities for improving efficiency and reducing costs in production". In summary, the author describes each of the chronoanalysis processes as a set of steps, according to the flowchart shown in Figure 10.

Figure 10. Chronoanalysis flowchart



Source: Adapted from Barnes, 1968

Each stage was fundamental for the success of the chronoanalysis and for identifying opportunities for improving efficiency and reducing costs in production.

4. RESULTS ANALYSIS

In previous academic studies on machining processes in the metalworking sector, it was inferred that the combination of different types of cutting tools offers parameters and strategies that allow improving machining performance in terms of time and cost.

In the chronoanalysis, the result of the standard time calculated based on the times recorded in the part's machining step, using the tool from Supplier 1, was 26.67 hours, and from Supplier 2, it was 5.02 hours. Therefore, the comparison between the two tools showed an increase in productivity from 3.75 pieces/hour to 19.91 pieces/hour, as shown in Figure 11, corroborating the findings in the literature.

Figure 11. Productivity comparison between tools

		Supplier 1	Supplier 2
Exchange Criteria		WEAR	WEAR
(1) Parts produced Jg. Edges / Sharpening		50	70
(2) Effective cutting time	min./piece	15,000	2,000
(3) Remaining time of the machining cycle	min./piece		
(4) Edge/tool change time.	min.	1,000	1,000
(5) Changeover time	min./piece	0.020	0.014
(6) Unproductive time	min./piece	1,000	1,000
(7) Machining Cycle Time (2)+(3)	min./piece	15,000	2,000
(8) Total operation time (5)+(6)+(7)	min./piece	16.020	3.014
Production 60/(8)	pieces/hour	3.75	19.91

Source: Authors (2023)

The tool life evaluation criteria in the applied visual test were verified from the wear of the burrs generated from the edge on the components and the dimensional changes detected after the machining process (Figure 12).

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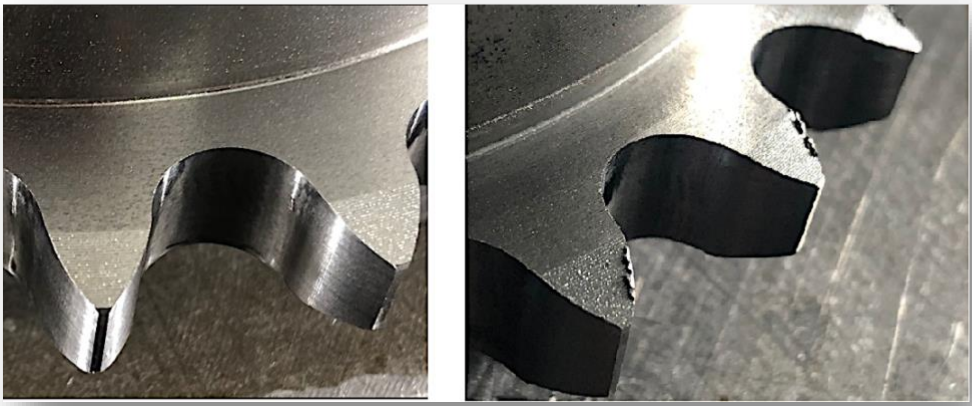
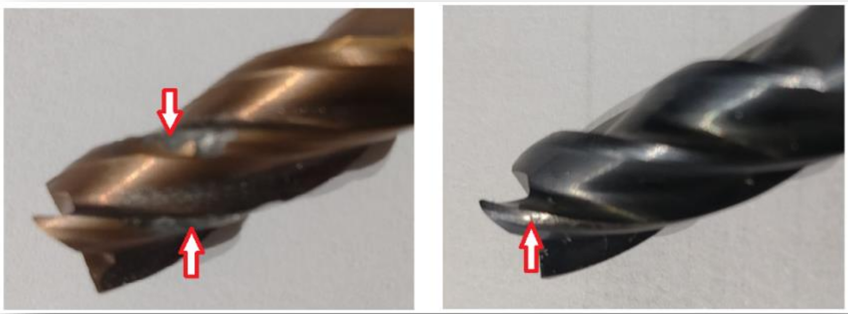
Figure 12. Visual comparison of machined tooth edges
Burr-free machined part Parts machined with burrs



Source: Authors (2023)

The tool from Supplier 1 supported the machining of 50 parts before the appearance of burrs, while the tool from Supplier 2 allowed the machining of 70 parts during the tests before the appearance of burrs. In Figure 13, it is possible to compare the wear present on the cutting edges of the milling cutters after use.

Figure 13. Visual comparison of cutter edge wear
Milling cutter Supplier 1 Milling cutter Supplier 2



Source: Authors (2023)

It could be verified in the comparison of the machining process improvements, as shown in Figure 14, that the proposal of Supplier 2 generated significant factors for immediate approval after the test was carried out, as the following data were found:

- Increased tool life by 40%;
- Reduction of total operating time by 81%;
- Increased productivity by 431%;
- Reduction in the cost per part by relating the investment of the tool to the quantity of parts produced.

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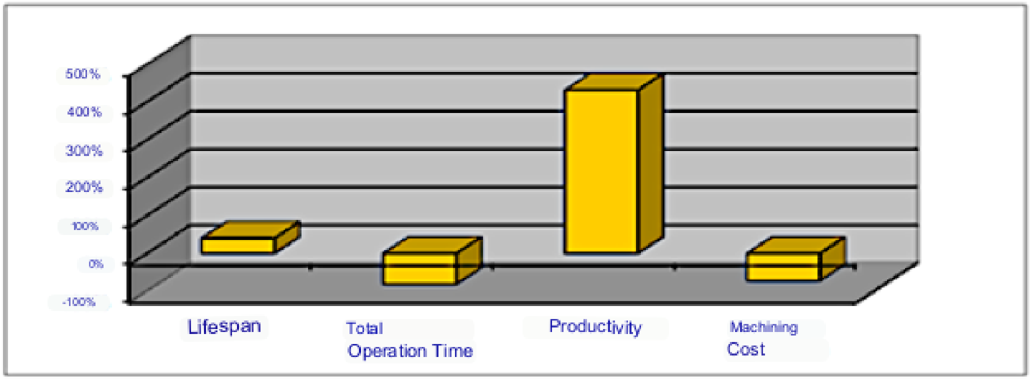
Figure 14. Comparison of improvements in the machining process

	SERVICE LIFE (Parts/Jg. Edge)	TOTAL OPERATION TIME (Min/Piece)	PRODUCTIVITY (Pieces/Hour)	MACHINING COST (R$/Piece)
SUPPLIER 1	50	02.16	3.75	41.75
SUPPLIER	70	3.01	19.91	11.74
2 RESULT	40%	-81%	431%	-71.9%

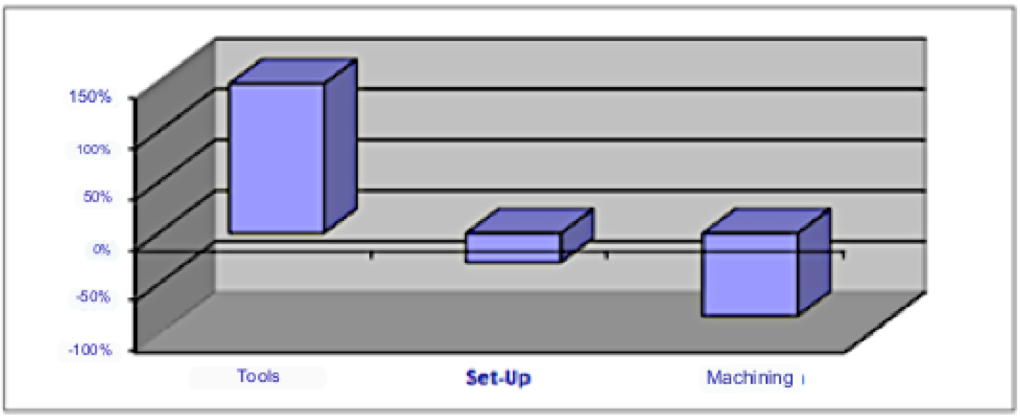


Source: Authors (2023)

In Figure 15, comparing the two scenarios, it can be seen that the increase in productivity had a positive financial impact and reduced the cost of investment in tools. In supplier 2's proposal, it is observed that the cost of the tool is 3.5 times higher than the current tool from supplier 1, but due to its performance, it provided significant improvements in the process and longer useful life, which contributed to the reduction the consumption of tools in the process, turning into savings.

Figure 15. Comparison of machining process costs

	TOOLS (BRL/year)	SET-UP (R$/year)	MACHINING (R$/year)	TOTAL (R$/year)
SUPPLIER 1	1,700.00	50.00	40.000,00	41,750.00
SUPPLIER 2	4,203.00	35.71	7,500.00	11,738.71
COST REDUCTION	147%	-29%	-81%	-71.9%



Source: Authors (2023)

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Finally, other costs involved in the machining process such as energy, lubricating oil, machine availability, personnel, tool change setup, etc. were also reduced, generating:

29% reduction with setup

81% reduction in machining cost;

Savings of BRL 30,011.29/year (72%).

5. FINAL CONSIDERATIONS

In this case study, the possibility of improving the machining process of a part called Turnstile, using different cutting tools, was evaluated. The results showed that the tool provided by Supplier 2 performed better than the tool provided by Supplier 1, resulting in significant improvements in the machining process.

Through this study, it was inferred that the combination of different types of cutting tools in the gear tooth milling process improved machining performance in terms of time and cost, in line with previous studies in the metalworking sector.

The results obtained proved that the implementation of Supplier 2's proposal generated significant improvements in the machining process. There was an increase in tool life, a reduction in total operating time, an increase in productivity and a reduction in the cost per part by relating the tool investment to the number of parts produced, in addition to indirect savings in other costs involved in the process such as power, lubricating oil, machine availability, personnel and tool change setup.

Some limitations must be considered in this study, such as the lack of analysis of other variables that may affect the machining process and the possibility that other types of tools may perform even better than those tested in this study.

The methods used in this study were suitable for the proposed objective, with adjustment of the machining parameters and assessment of tool life based on the wear of the generated burrs and the dimensional changes detected.

Considering all these points analyzed and their relevance, it was suggested that the company implement training among suppliers and employees on types of cutting tools and their applications.

For future studies, it is suggested the analysis of other variables that may affect the machining process, such as the geometry of the part and the composition of the material used. In addition, it is suggested the analysis of other cutting tools and the evaluation of their performance in different types of machining.

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