

# REVISTA AIDIS

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Investigación, desarrollo y práctica.

## ENERGY, ENVIRONMENTAL AND FINANCIAL EVALUATION OF PROGRESSIVE CAVITY PUMPS WITH ROTORS PRODUCED FROM DIFFERENT MATERIALS

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### Abstract

*In industrial applications, pumps traditionally operate for thousands of hours at high pressures, often under severe conditions imposed by abrasive fluids or undergoing chemical attack. However, in tinting dispensers, a progressive cavity pump (PCP) rarely reaches one hundred hours of use, and alternative materials could be explored for its components. An energetic, environmental, and financial assessment was conducted on four distinct materials intended for the rotor of a PCP: chrome-coated steel, PA6, PEEK, and 6082 aluminum alloy. Equipment was built to obtain the characteristic curves of each pump, electrical energy consumption, wear of rotors and stators, and energy efficiency. The rotor machining process was instrumented to measure electrical energy and inputs. The Cleaner Production method was applied, and, finally, the rotors underwent financial evaluation. There was no significant wear on the stator-rotor pairs, the minimum lifetime was not a challenge for the integrity of any of the components, and the polymers studied were not incompatible with the working fluid. Maximum and minimum energy efficiency of the pumps occurred with aluminum alloy and PA6 rotors, respectively, showing a difference of 22.5% in electrical energy consumption. However, the PA6 rotor presented the best energy and environmental efficiency in the manufacturing process, in addition to being the only one capable of dry machining. Financially, all proposed materials registered a significant improvement, particularly highlighting the aluminum alloy and PA6 rotors, which exceeded a 90% cost reduction.*

**Keywords:** progressive cavity pump, energy efficiency, cleaner production, tinting.

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## Introduction

The tinting system emerged in the United States and Europe in the 1970s and arrived in Brazil in 1992, when the production of paints was no longer exclusive to the industry and began to be shared with specialized retailers. The encouragement of conscious consumption, through the National Solid Waste Policy, in Brazil, was one of the main reasons that subsequently pressured the sector towards this model in which the retailer became a manufacturing unit of colored paints.

The process currently consists of the consumer choosing a color from a specific product line (matte, gloss, semi-gloss, etc.) and a can size, according to their needs, from a catalogue. The retailer consults the information in the formula database to dose the colorants in the can containing the neutral paint. After dosing, the can is shaken for the necessary time until the product is homogenized, traditionally, in a gyroscopic mixer. Typically, dispenser machines operate with 3 to 4 neutral paints and 12 to 16 colorants, depending on the paint manufacturer, which when mixed generate the most varied combinations of final colors, reaching a total of ten thousand. (Análise, 1998; Linhares, 2018; Monfardini, 2013; Zaparolli, 2009).

The tinting system requires the dispenser to reproduce precise and accurate dosages. Therefore, positive displacement pumps are recommended for this application, such as piston, bellows, gear, progressive cavity pumps, among others, also called volumetric pumps, which keep the fluid confined and dose fixed quantities per cycle. These pumps, for dosing colorants, are exposed to a situation of low use of mechanical force, small pressure differential, very low abrasion, and chemical attack of the fluid. Therefore, there is less attack on the integrity of the components, compared to most applications, such as in the oil industry, which shares the applicability of progressive cavity pumps, where the damage to the components is very high. The *PCP* consists of a rotor in the form of a helical screw and a stator made of vulcanized elastomer, natural or synthetic, specified depending on the chemical composition and temperature of the fluid to be pumped (Henn, 2006). The performance and efficiency, in the oil industry, working with extremely abrasive high viscosity oils has consolidated materials, coatings and manufacturing processes of the fundamental components: rotor and stator. Given the significant development of the tinting system in Brazil, improvements in energy efficiency have the potential for large-scale expansion.

The study aims to evaluate different materials applied to the rotor of a progressive cavity pump, used in this industry or system, to improve energy consumption in the production process, environmental and financial benefits, increase pumping efficiency and quality and reduce maintenance costs.

### Automatic paint tinting dispensers

Automatic tinting dispensers are equipment that have a computer to access the paint manufacturer's formula database and perform the dosing of colorants using positive displacement pumps, which dose the same quantity per cycle or revolution. Currently, pumps such as piston, bellows, gear, and progressive cavities are used, equipped with controlled drive, which is, using stepper motors, servos, or encoders, which monitor their positioning and control the dosed volume.

Figure 1 illustrates the main components of the tinting system in a dispenser: colorants stored in the reservoirs and the can containing neutral paint positioned for dosing (Geltint, 2018).



**Figure 1.** Main components of the automatic paint tinting dispensing system (Geltint, 2018).

Tinting machines make a significant contribution to the environment. There is no unnecessary consumption of raw materials, energy and inputs for paint production and storage. This equipment allows the entire distribution chain to work with less stock, as it allows the preparation of paints within the store. In the logistical context, there is less needed to transport ready-made paints to points of sale, reducing fuel consumption and emissions (Ferreira, 2015).

Tinting colorants are concentrated products used in small quantities to produce the final color, compared to the volume of neutral paint contained in the can. Some formulations use less than 1% of colorant of the total paint volume. Therefore, a pump will not reach a total dosage of 1000 liters of colorant throughout its existence in a conventional point of sale.

Progressive cavity pump (PCP)

The PCP is basically formed by a rotor with a profile of  $n$  helical cylindrical teeth and pitch  $p$ , which rotates in relation to the stator, fixed to the pump housing, with an internal cavity with a profile of  $n + 1$  cylindrical teeth and pitch  $2p$ . Simultaneously with the rotation, the rotor prescribes an eccentric cyclic movement, following a trajectory that varies with the value of  $n$  (Aage *et al.*, 2006; Chen *et al.*, 2013; Gravesen, 2008).

In the classic configuration illustrated in Figure 2, when  $n = 1$ , the PCP has a helical cylindrical rotor, an elastomeric stator with an oblong helical internal cavity and the center of the rotor prescribes a hypocycloid trajectory (Nguyen *et al.*, 2016). The rotor rotates eccentrically within the stator, so the fluid is moved helically throughout the pump. Figure 3 illustrates this shift (Whittaker, 2003).

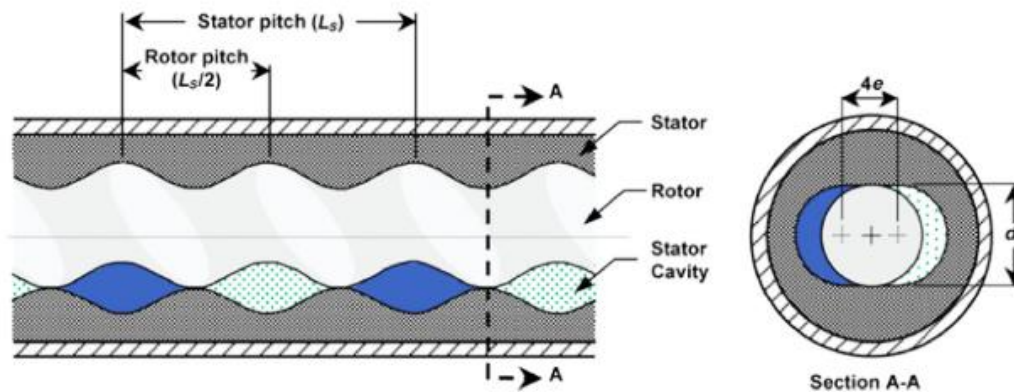


Figure 2. Longitudinal and transverse sections in a stator-rotor pair (Nguyen *et al.*, 2016).

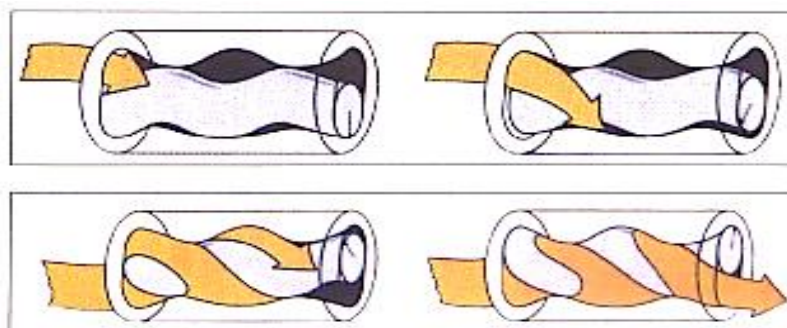


Figure 3. Fluid displacement in the cavities formed by the stator-rotor pair (Whittaker, 2003).

Four main parameters characterize a *PCP*. Three parameters refer to the cross-sectional area of the pump, which is determined by the rotor diameter, eccentricity and interference or clearance. The fourth parameter is the stator pitch. When the section area covers the stator pitch, the volume displaced in one revolution is obtained. (Pessoa, 2009). The stators can be rigid or flexible and define completely different characteristics for the *PCP*, such as tightness, which is not covered by rigid stators and is not acceptable in tinting dispensers. For most applications, the following elastomers stand out: nitrile rubber (NBR) with medium and high concentrations of acrylonitrile (ACN), hydrogenated acrylonitrile butadiene rubber (HNBR) and fluorinated rubber (FKM), commercially known as Viton.

Rotors are traditionally manufactured from electroplated hard chromium-coated steel or tungsten carbide, or solid stainless steel and silicon carbide. To enable the manufacture of helical geometry, it is necessary to add to traditional machining a process with a rotating tool, called whirling, synchronized with the movement of the other axes of the lathe, limiting this operation only to computerized machining equipment.

The nominal flow of the *PCP* is obtained by multiplying the theoretical volume displaced by the angular speed of the motor shaft. By subtracting the slip, the real flow is obtained. By making the quotient of the real flow with the nominal flow, the volumetric efficiency of the *PCP* is obtained (Chaparro Fonseca, 2008). The two potential slip mechanisms in the pump are depicted in Figure 4: longitudinal and transverse (Paladino *et al.*, 2008). The total efficiency of a pump is evaluated through the theoretical power, which quantifies the variation in the fluid work, divided by the real power consumed, measured by the product of the torque and angular speed of the motor shaft or the voltage and electric current supplied to the motor. This efficiency represents the overall performance of the set formed by all pump components (Pessoa, 2009).



Figure 4. Representation of the slip mechanisms of a *PCP* (adapted from Paladino *et al.*, 2008).

### Whirlwind milling process

Most machining operations use lubricant, also known as cutting fluid, which makes the metalworking industry a potential environmental aggressor. They generate harmful effects on the work environment and significant environmental impacts (Oliveira and Alves, 2007).

The Bergsmuller Company created the whirlwind milling process in Germany. It consists of a rotating tool holder with cutting inserts that encloses and removes material from the workpiece, held in the head, which moves, at a certain rate, along the longitudinal axis to produce a helical shape (Mohan and Shunmugam, 2007; Song and Zuo, 2013). In Figure 5, a whirlwind and its kinematic parameters are schematically illustrated (Serizawa and Matsumura, 2016). A variable that represents the energy efficiency of the process and is subject to the influence of machining conditions, the material of the part, and the cutting tool is the specific cutting energy, which is also understood as the ratio between specific cutting power and the material removal rate, equivalent to energy per unit volume (Rigatti, 2010; Souza, 2011).

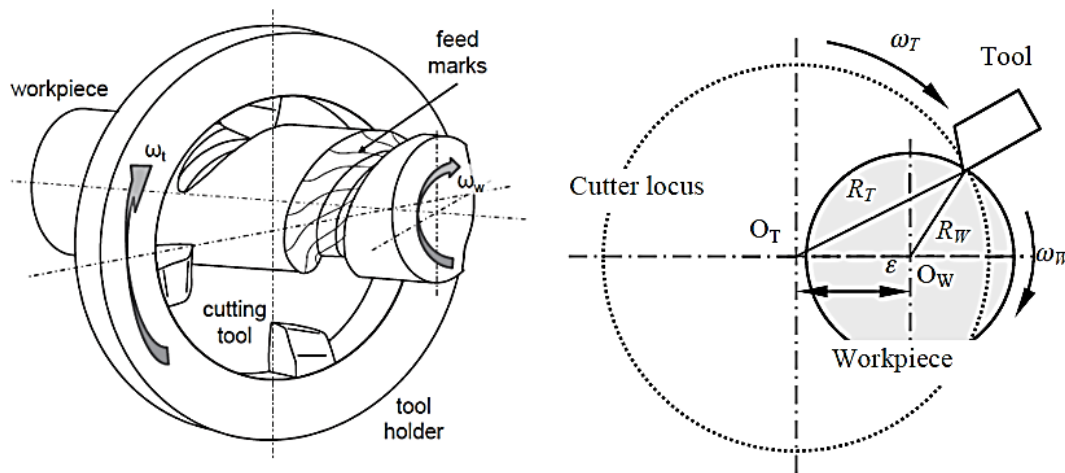


Figure 5. Illustration of the whirlwind milling process (adapted from Zanger *et al.*, 2017 and Serizawa and Matsumura, 2016).

### Cleaner production method

Methodologies such as Cleaner Production (CP) emerged from the evolution of the way of thinking in the context of environmental impacts. Preventing pollution consequently leads to continuous improvement in processes instead of managing the waste generated. CP presents a detailed analysis of the production process through the quantification of inputs, energy used and environmental impact, while conventional methods, called end-of-pipe, focus only on the treatment of final waste. The CP technique consists of avoiding or minimizing all waste (Medeiros *et al.*, 2017).

The application structure of the CP methodology is divided into three levels, illustrated in Figure 6. The first two focus on minimizing waste and emissions and the third on their reuse or external recycling. Level 1 deals with waste reduction, and improvements consist of changes to the product or production process. Level 2 refers to internal recycling, reintegrating waste from the production process into components made from the same raw material with the same or lesser purpose than the original. If it is impossible to reintegrate the waste, a means of external recycling is sought; seek destinations and resources outside the company for their treatment, covered in level 3.

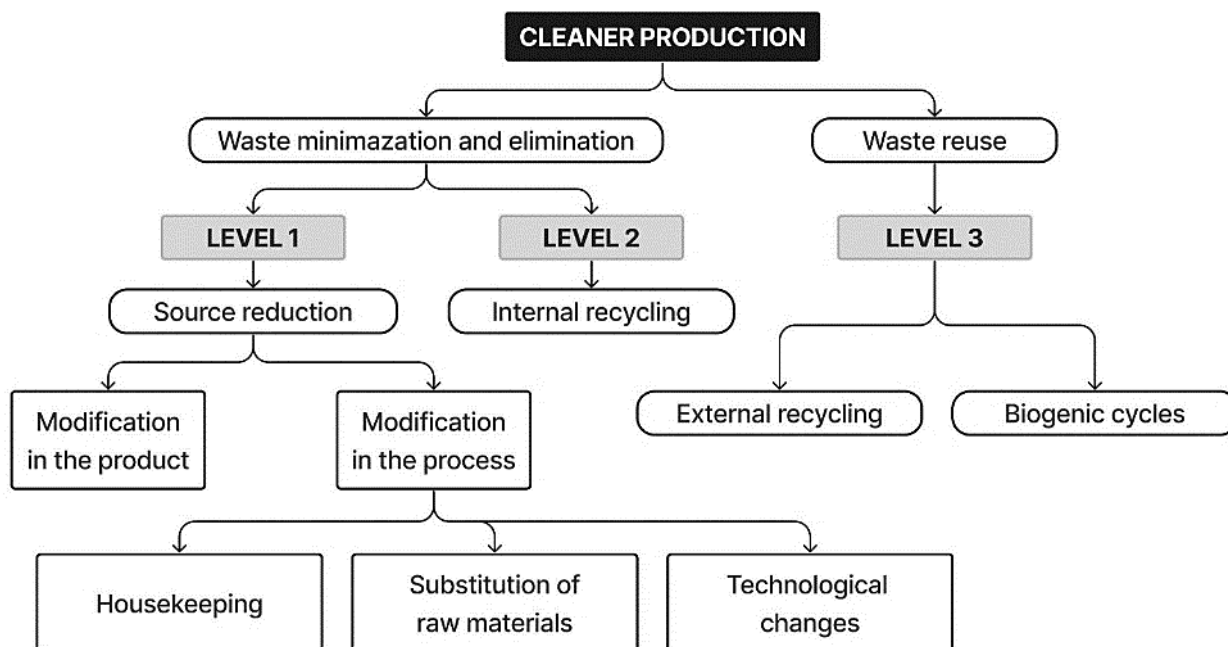


Figure 6. Levels of the CP methodology (adapted from Oliveira and Alves, 2007).

### Methodology

Methodologies such as CP emerged from the evolution of a way of thinking in the context of environmental impacts. Preventing pollution consequently leads to continuous improvement in processes, instead of managing waste generated.

### Materials

The rotors used in the study were manufactured, through the whirlwind milling process, in the dimensions of the pump's original design, from four different materials: SAE 12L14 chrome-plated

desulfurized steel, currently used in in Percolore brand machines, Polyamide 6 (PA6), PEEK and 6082-T6 Aluminum Alloy. Figure 7 shows the manufacturing drawing of these parts. FKM (fluorinated elastomer) stators were used, as shown in Figure 8. They were produced through vulcanization under pressure in a closed mold.

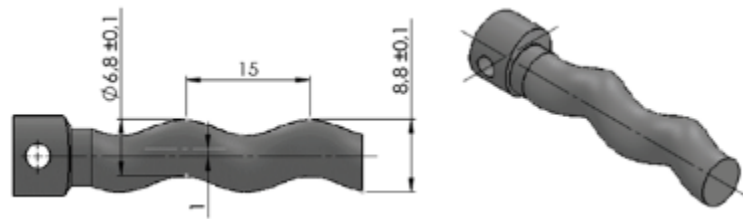


Figure 7. Original Percolore brand PCP rotor design (created by author).

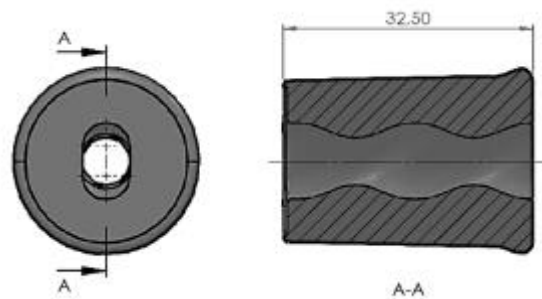


Figure 8. Original Percolore brand PCP stator drawing (created by author).

A precision scale, model S423 by BEL, was utilized to measure the mass of the rotors and stators. The scale had a resolution of  $0.001\text{ g}$  and an accuracy of  $\pm 0.004\text{ g}$ . This measurement is employed to assess wear and facilitate comparison with the final mass. The dimensions of the rotors were determined using a digital caliper with an accuracy of  $\pm 0.02\text{ mm}$  and a resolution of  $0.01\text{ mm}$ . This enabled the determination of the rotors' cross-sectional diameters,  $dR$ , as well as the external diameter of the helicoid, which represents the largest diameter of the rotor. In order to determine the nominal volumetric flow of each pump, these values are utilized.

After manufacturing each stator-rotor pair and the other components that are part of the PCP, shaft, gasket, retainer, etc., the twenty-four pumps that were evaluated in this work were assembled. This pump, used in tinting dispensers from the Percolore brand, a research partner, has a rotor and stator configuration for one stage, is equipped with a stepper motor and operates with an angular speed of 400 *rpm* and an average flow rate of 280 *ml/min*, both nominal quantities. Figure 9 shows the pumps.



Figure 9. Percolore brand PCP (created by author).

#### Assessment of polymers and tinting material

The density and viscosity values of the tinting colorant E - 96-5 Blue were verified as they are necessary parameters for calculating the volumetric efficiency. Its density was assessed according to the ABNT NBR 5829 standard (2014), with a 100 *ml* pycnometer and viscosity by consulting the technical sheet of the respective fluid. The evaluation of the interaction of the tinting colorant with the polymers was guided by the ASTM D471 standard. Basically, the polymeric rotors had their masses evaluated and then immersed in a container with the fluid, individually. After the time determined by the standard, which for this application was 70 hours, the parts were removed and underwent mass evaluation again. A specimen of each material was used.

#### Data collection from the rotor machining process

The electrical consumption for machining each type of rotor was evaluated, that is, each of the four materials under study: SAE 12L14 steel, 6082 aluminum alloy, PA6 and PEEK. For the evaluation, digital multimeters were used to measure the electrical current and voltage of each tool on the CNC lathe to calculate the power later. The usage times for each tool were obtained from the cutting program (CAM) that controls the process. From the power and time of each operation on the lathe, the energy consumed in each operation was calculated for each rotor material. Finally, the total energy consumed to manufacture the rotor is the sum of the energy

consumed in each operation or tool. The need to use cutting fluid was evaluated for machining each of the four materials, based on the quality of the surface finish obtained. The use of cutting fluid increases electrical consumption, described in the previous item, because it activates a pump for its recirculation.

#### Energy efficiency evaluation

An assessment of energy efficiency was carried out throughout the rotor production chain and the work performance of *PCPs*. The analysis of the machining efficiency of the rotors was based on three parameters: material removal rate, specific whirl cutting energy and total specific cutting energy. The efficiency of the *PCP* was evaluated by three parameters, throughout the useful life: volumetric, mechanical, and total.

#### Environmental assessment, identification of opportunities for the CP methodology

The rotor manufactured from different materials was evaluated using the CP Methodology. Focusing on rotor manufacturing, opportunities for improvement in the process were compared, according to the CP structure, for the four different materials. Through a flowchart of the rotor manufacturing process, the inputs and outputs of energy and materials were documented, and waste and the cause of its generation were identified to suggest improvements.

#### Financial assessment

The cost of the raw material was obtained from the quotations and purchase of round bars with a diameter of 3/8" (9.525 mm) to produce the rotors and the cost per meter of each material was compared. The cost of the rotor manufacturing process was evaluated through the energy consumed in machining each rotor multiplied by the value of the local supplier's electrical energy. The cost of machining inputs used data from the machining process of the SAE 12L14 steel rotor as a reference. In the specific case of the SAE 12L14 steel rotor, the cost of the chrome coating currently used on the component was increased. The other materials do not use this coating and did not have this value added.

### **Results and discussion**

The results are presented separately to facilitate interpretation. At the end, a table presents the relevance of each result, in a qualitative way, for comparing the materials studied.

#### Production, metrology of rotors and stators, and assembly of pumps

All rotors and stators presented measurements in accordance with the dimensional tolerance determined by the pump design. In Figure 10, all test specimens are shown.



**Figure 10.** Rotors and their respective FKM stators. a) Chrome-plated SAE 12L14 steel rotors; b) PA6 rotors; c) PEEK rotors; d) 6082-T6 aluminum alloy rotors (created by author).

The steel rotors presented the highest standard deviation, due to the greater cutting force which, consequently, generates greater vibration and instability in the process. PA6 rotors showed improved dimensional stability compared to steel because they require less cutting force. Using PEEK as materials, the rotors recorded worse dimensional stability results, compared to PA6. Aluminum, on the other hand, recorded the highest dimensional stability and accuracy among the four materials. The averages were  $6.78\text{ mm}$  for the rotor cross section with  $0.01\text{ mm}$  standard deviation and  $8.81\text{ mm}$  for the largest rotor diameter, repeating  $0.01\text{ mm}$  standard deviation. The stators underwent mass assessment to subsequently support wear measurements after use. The average was  $19.431\text{ g}$  and the standard deviation was  $0.201\text{ g}$  and it was found that more than 80% of the stators have  $19.270\text{ g}$  and  $19.510\text{ g}$ . Figure 11 shows the 24 pumps assembled with the test specimens presented in Figure 10. The assembly of each one followed the same procedure, and all other components are the same, that is, their only differences are exclusively the stator and rotor pair.



**Figure 11.** Image of the Percolore brand pumps assembled with its respective label indicated the test specimen (created by author).

#### Physical properties of tinting colorant and polymer resistance

Three measurements were taken in a 100 ml pycnometer, according to the ABNT NBR 5829 (2014) standard, to determine the specific mass of the colorant. After calculating the average, the value of 1.4365 g/ml was obtained, which represents a 3.75% difference in relation to the value reported in the technical sheet, which also informs that the viscosity is approximately 3 Pa.s or 3000 cP. The polymers studied for the rotors, PA6 and PEEK, and the stator, FKM, underwent evaluation of resistance to the absorption of tinting colorant, in accordance with the ASTM D471 standard. The values were negligible, less than 0.1%, showing that the three materials have excellent resistance to the colorant in this study.

#### Electrical consumption of PCPs

The total power is directly proportional to the torque used by the pump to perform work on the fluid. Therefore, it illustrates the behavior of the stator-rotor contact interface and, consequently, is influenced by its materials. To facilitate interpretation, averages of behavior were taken over the total number of revolutions of each type of pump and displayed on the graph in Figure 12.

It was observed that the greatest power requirement comes from pumps with PEEK rotors, which reduces in the following order: SAE 12L14 chromed-plated rotors, 6082-T6 aluminum and PA6, which recorded the lowest demand. To compare the energy consumed by each type of pump, the dosage volumes and their respective powers were evaluated at each evaluation point (100 thousand revolutions, 200 thousand revolutions, etc.) and at the end of 1 million revolutions they

were extrapolated the flow and power results until reaching 1000 liters to obtain the total estimated working time to reach this volume. Therefore, these results consider the variation in pump power and flow throughout its use. Figure 13 presents the results. Therefore, in terms of electrical consumption, the aluminum rotor obtained the best result, registering 755 Wh to dose 1000 liters of colorant, while the PA6 rotor obtained the worst performance, registering 925 Wh for the same volume. This occurs because this polymer has lower volumetric efficiency than the aluminum rotor. In this way, it produces a lower flow rate for the same power, that is, it requires more time of use to reach the same final volume and, consequently, greater electrical energy consumption.

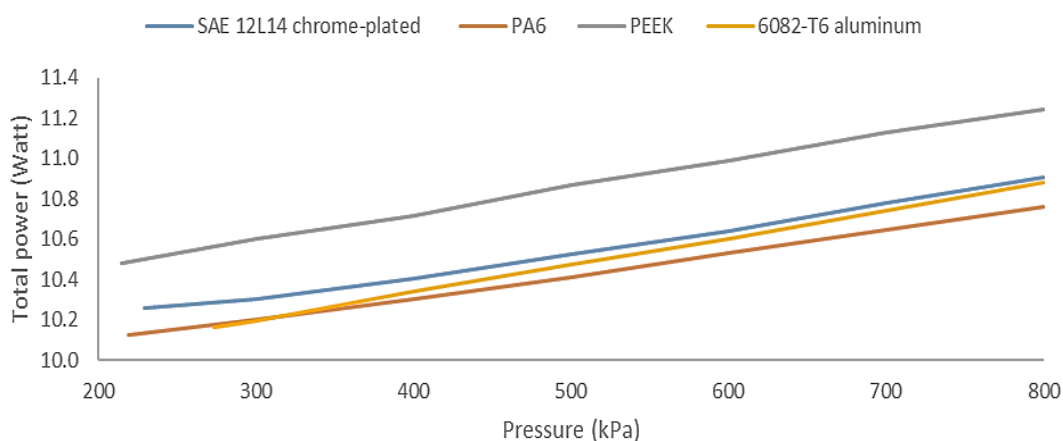


Figure 12. Average total power of PCPs assembled with each rotor material.

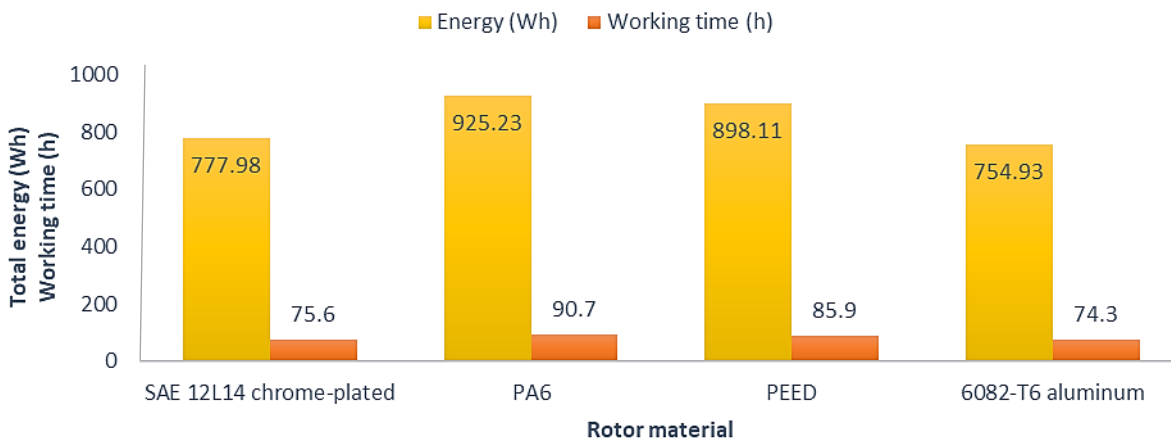


Figure 13. Energy and time consumed to dose 1000 liters of colorant.

### Electrical consumption of rotor machining

The steel rotors require greater power to move the axes and machining tools, due to the greater cutting force compared to aluminum and, mainly, to the two polymers. Furthermore, the machining of the PA6 rotors did not require cutting fluid on the lathe used, which eliminated this portion of energy from total consumption, in addition to reducing the generation of liquid effluent.

Figure 14 presents a detailed comparison of the total energy consumption for each material. It is evident from the results that the whirlwind is the instrument that is most susceptible to the type of material being machined. This behavior was anticipated, given that the primary machining operation performed on the rotor was grinding the gross diameter between 9.525 mm and 6.8 mm. PA6 rotors had the lowest overall consumption, followed by PEEK, 6082-T aluminum, and SAE 12L14 rotors.

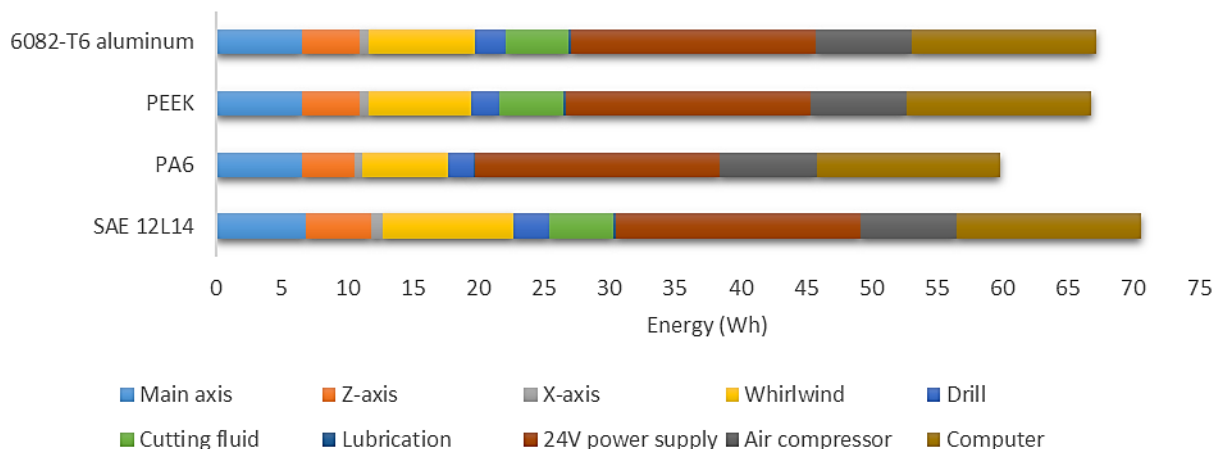


Figure 14. Comparison of energy consumption when machining different materials.

### Rotor machining efficiency

Specific machining energy uses values of the material removal rate, measured in volume and time, and electrical consumption of the process, to generate the result in terms of electrical energy consumed in relation to the volume of material machined, as an indicator of efficiency. The results are shown in Figure 15. The SAE 12L14 rotors had the highest specific machining energy, that is, they have the highest electrical energy consumption per volume of material machined. This behavior was expected since this material requires the highest cutting force among the four studied.

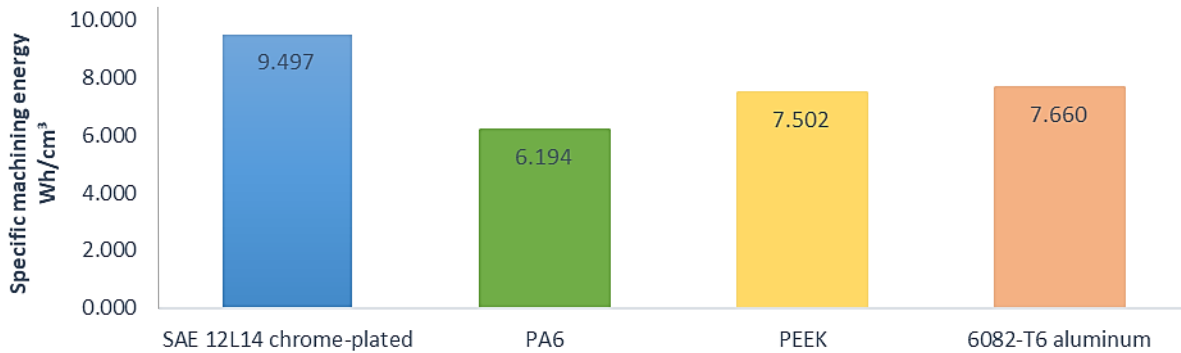


Figure 15. Specific machining energy of different materials.

### Energy efficiency of PCPs

The comparison between the average volumetric efficiencies is shown in Figure 16. The lower performance of polymeric rotors and the similarity between steel and aluminum are clearly seen, with a slight superiority of aluminum. The volumetric efficiency range in which the *PCP* with a PA6 rotor operates is the smallest, followed by the PEEK *PCP*, with the aluminum and chromed steel *PCPs* exhibiting the highest results, between 74.5 and 80.5%. A significant outcome, particularly within the tinting sector, was the minimal fluctuation in volumetric efficiency observed at the conclusion of one million cycles of the *PCP*. The colors produced are stable since their variations are less than 2% of the dosed volume, which is an indication of their excellent performance.

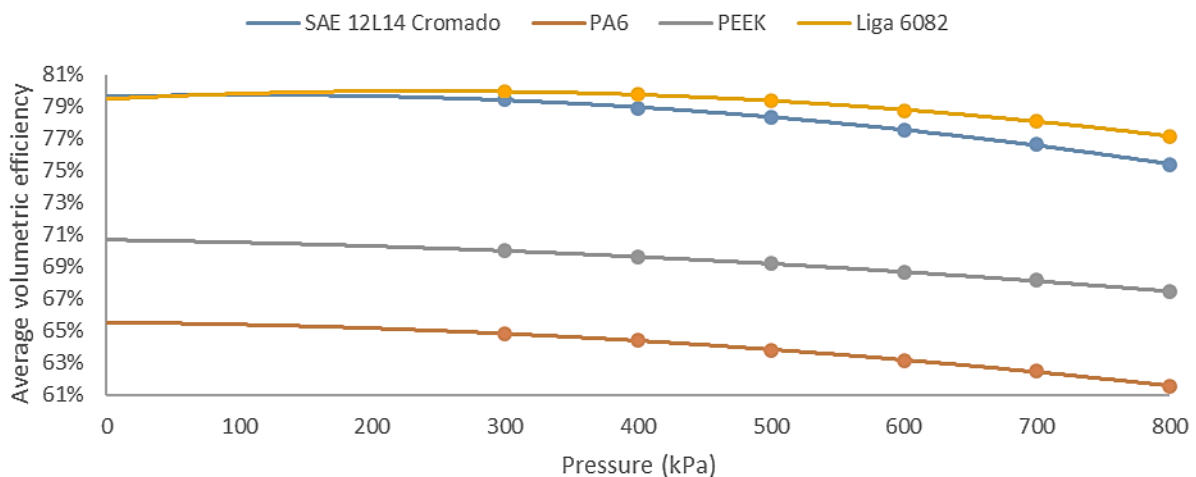


Figure 16. Comparison between average volumetric efficiency of *PCPs*.

The global efficiency results of the *PCPs* are shown in Figure 17. Like the volumetric efficiency, the total efficiency showed a large discrepancy between the polymeric rotors in relation to chrome-plated steel and aluminum.

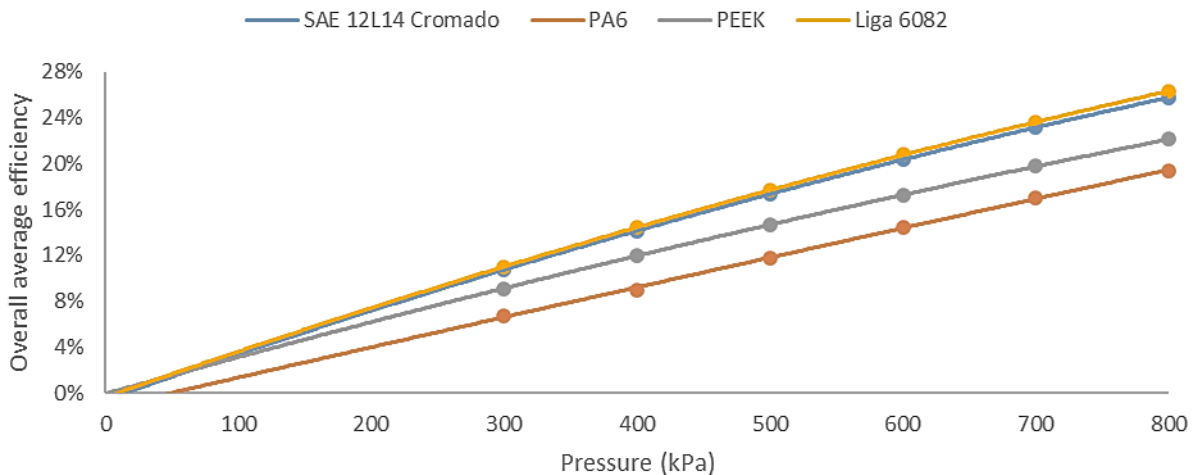


Figure 17. Comparison between average global efficiency of *PCPs*.

At low pressures, progressive cavity pumps with elastomeric stators operate at a suboptimal overall efficiency, which is primarily attributable to interference in the rotor and stator assembly. To induce elastic deformation and friction at the interface of these components, a substantial amount of electrical drive power is required. Consequently, the effort required to pressurize the fluid at low pressures is negligible in comparison to the mechanical effort required to rotate the pump.

As the pressure within the *PCP* increases, it effectively reduces the electrical power required for its mechanical operations. This results in improved overall efficiency and more efficient utilization of the power supply. The results indicate how energy is dissipated mainly due to the inadequate design of the *PCP*, that is, the interference between the stator and the rotor, in the friction generated at the interface, in the mechanical transmission, among other items.

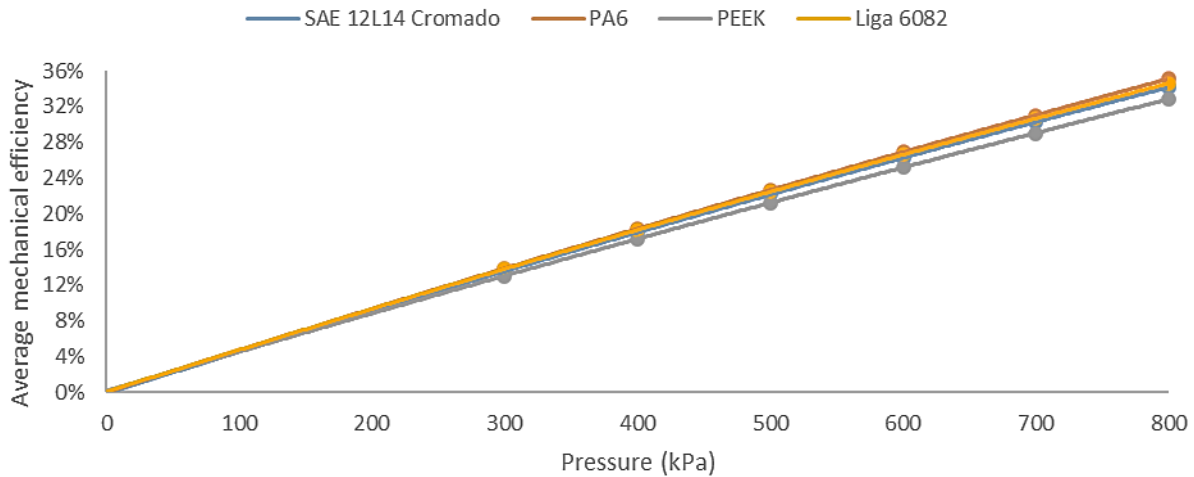


Figure 18. Comparison between average mechanical efficiency of PCPs.

### Cleaner production methodology

The flowchart of the rotor manufacturing process is shown in Figure 19, which shows the inputs, operations, and outputs as a basis for evaluating improvement opportunities: source reduction, internal recycling, and external recycling. The results of the improvement potentials are shown in Table 1. It presents the applicability of each material for the CP group, their respective benefits, barriers, and opportunities.

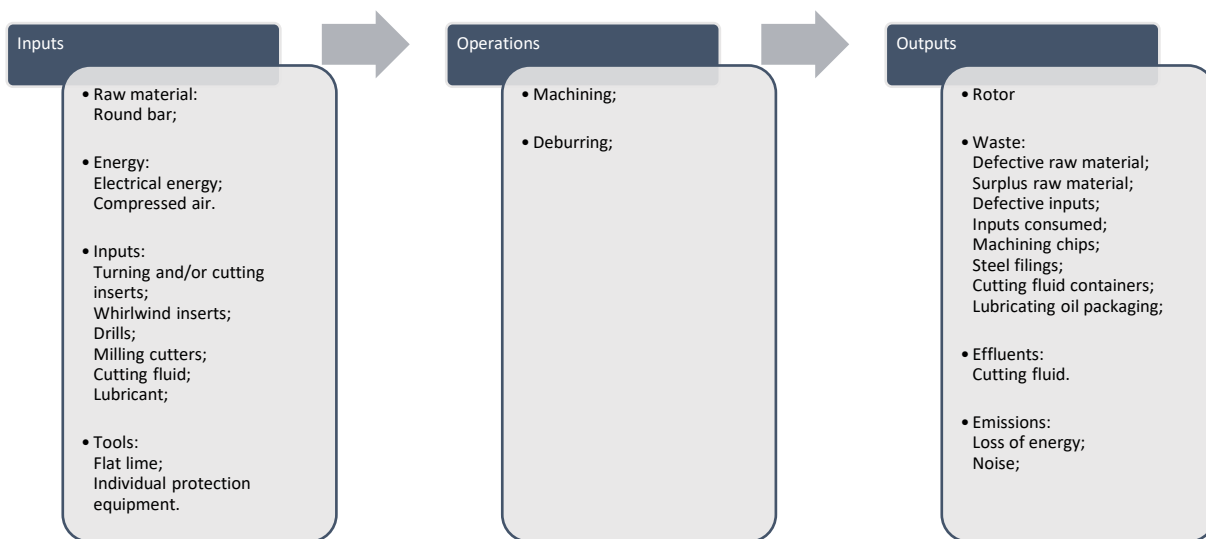


Figure 19. Flowchart of the rotor manufacturing process.

### *Source reduction*

One way to improve the rotor is to optimize the maximum diameter or reduce the eccentricity of the helicoid, which would consequently result in less material being removed. Those would reduce the pump cavities and nominal flow, requiring a detailed assessment of the feasibility of the change. This change would result in less solid waste generation. For the machining process, the most relevant environmental impact comes from the use of cutting fluids. Therefore, when modifying the process, possibilities for improvement focused on these fluids were raised based on the three alternatives suggested by the methodology: housekeeping, replacement of raw materials, and modification of technology.

Preventive measures can be taken to select the fluid, for example, requiring suppliers to guarantee their origin, assistance, and support for their management. When using fluids, there are opportunities such as adjusting flow parameters and direction of the jet on the part, training employees to avoid contamination, and developing hygiene habits. These fluids can be recovered and treated; there are ways to improve the recovery processes, including evaluating their efficiency, controlling concentration and pH according to the manufacturer's recommendations, and observing the quantity and quality of the water used for dilution, among others. It could also be evaluated using the Minimum Quantity Lubrication (MQL) technique, which uses compressed air to spray only the necessary amount of fluid to reduce friction between the part and the cutting tool.

Another technique to be analyzed is dry machining. This method has advantages such as eliminating the cost of cutting fluid, while it presents challenges such as the need for greater rigidity in the lathe and its tools. The material must resist imposed thermal gradients and the use of special machining tools. In the case studied, it was possible to use this technique without modifications to the equipment, only on the rotors.

### *Internal recycling*

For machining, the best option would be to recover and recycle the cutting fluid used to remove oil, dirt, and bacteria and adjust its concentration, providing conditions for it to return to the process (Oliveira and Alves, 2007). The high cost of an implementation like this makes it justifiable to apply only to companies specializing exclusively in machining. Figure 20 illustrates a cutting-edge fluid recovery system.

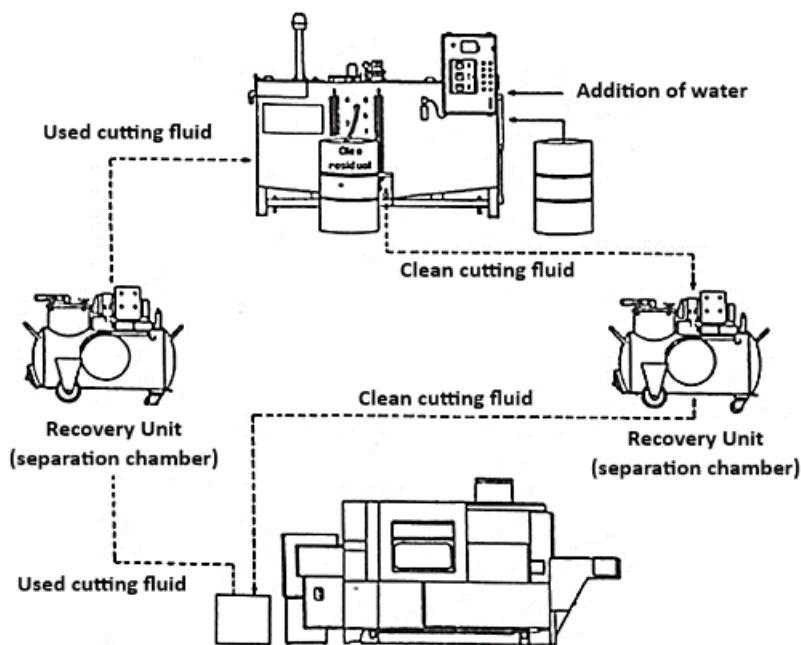


Figure 20. Cutting-edge fluid recovery system (adapted from Oliveira and Alves, 2007).

### External recycling

The chips and filings, after filtering the cutting fluid, can be sold externally, for example, in the case of metallic materials, directly with steel companies that reuse steel in electric arc furnaces or indirectly through scrap dealers. The same can be done with leftover raw materials, inserts, and machining tools.

Table 1. Opportunities for improvement using the CP methodology (continues)

| CP group             | Description                                     | Applicability |     |      |         | Benefits                                 | Barriers  | Viability                                      |
|----------------------|---|---------------|-----|------|---------|--|---|--|
|                      |   | SAE 12L14     | PA6 | PEEK | 6082-T6 |  |   |  |
| Product modification | Reduction of difference between rotor diameters | X             | X   | X    | X       | Reduction of chips, solid waste          | Modification in design, limitation of rotor application in some cases | Unfeasible, high functional impact of the pump |
|                      | Reduction of helicoid eccentricity              | X             | X   | X    | X       | Reduction of chips, solid waste          | Change in design, reduction in nominal pump flow                      | Unfeasible, high functional impact of the pump |
| Housekeeping         | Preventive selection of cutting fluid           | X             |     | X    | X       | Supplier handling assistance and support | Cost, difficulty in finding a guaranteed supplier                     | Viable, low investment                         |

**Table 1.** Opportunities for improvement using the CP methodology (*continuation*)

| CP group                     | Description   | Applicability |     |      |         | Benefits  | Barriers   | Viability   |
|------------------------------|---|---------------|-----|------|---------|---|--|---|
|                              |   | SAE 12L14     | PA6 | PEEK | 6082-T6 |   |  |   |
| Housekeeping                 | Preventive selection of cutting fluid                             | X             |     | X    | X       | Supplier handling assistance and support                        | Cost, difficulty in finding a guaranteed supplier            | Viable, low investment                            |
|                              | Adjustment of flow parameters and cutting fluid direction         | X             |     | X    | X       | Cutting fluid reduction, effluent reduction                     | Employee training  | Viable, low investment                            |
|                              | Hygiene habits with cutting fluid                                 | X             |     | X    | X       | Employee health   | Employee training  | Viable, low investment                            |
|                              | Avoid contamination of cutting fluid                              | X             |     | X    | X       | Effluent reduction  | Employee training  | Viable, low investment                            |
|                              | Recovery and treatment of cutting fluids                          | X             |     | X    | X       | Effluent reduction  | Cost, equipment implementation, employee training            | Unfeasible, high investment, high cultural impact |
| Substitution of raw material | Replacement of cutting fluids with those of vegetable composition | X             |     | X    | X       | Biodegradable, employee health, effluent reduction              | Cost, limited applications                                   | Viable, high investment                           |
| Technology modification      | Application of the MQL method to cutting fluids                   | X             |     | X    | X       | Cutting fluid reduction, effluent reduction                     | Cost, equipment deployment, mist emission                    | Viable, low investment, low cultural change       |
|                              | Dry machining   |               | X   |      |         | Effluent disposal, in accordance with environmental legislation | Rigidity of the equipment, need to change the rotor material | Unfeasible (except PA6), high investment          |
| Internal recycling           | Cutting fluid recovery  | X             |     | X    | X       | Effluent reduction  | Cost, equipment implementation                               | Unfeasible, high investment, high cultural impact |
| External recycling           | Sale of chips, raw material scraps, machining inserts             | X             |     |      |         | Waste reduction, conscious disposal, financial return           | Training suppliers for collection, search for partners       | Viable, low cultural impact                       |
|                              | Sale of used cutting fluid  | X             |     | X    | X       | Effluent reduction, conscious disposal, financial return        | Training suppliers for collection, search for partners       | Viable, low cultural impact                       |

### Costs

The four materials use round bars as raw materials for subsequent machining. The cost of this material was obtained at the time of purchase for manufacturing the respective test specimens used in this work. SAE 12L14 records the lowest value per kilogram. However, their rotors are not the cheapest, as they have the largest masses due to their greater density. Polymers occupy the

two extremes of final value between materials, with PA being the lowest value and PEEK being the highest. This, in a proportion more than 100 times greater, as it is a high-performance polymer, although it was not efficiently applied to the PCP rotor. And 6082-T6 aluminum positioned itself as third on the rising cost scale.

The costs of the machining process include electrical energy and inputs such as tools, machining inserts and cutting fluid. The cost of tools and inserts, and their respective productivity for machining each material, were obtained according to data from the company's machining process. From this data, the cost of these inputs for each rotor is found, which together with the consumption of electrical energy and cutting fluid makes up the total machining cost. The cost of cutting fluid per rotor was obtained through the value of a 20-liter package of the product, divided by 15,000 rotors, which represents the maximum production capacity allowed for this volume of product. This value was applied equally to the three materials that used the fluid: SAE 12L14, PEEK, and 6082-T6 aluminum.

Figure 21 illustrates the share of each class in the total cost. The SAE 12L14 chrome-plated rotor reached the highest cost, mainly influenced by its coating. Following in descending order, the PEEK rotor, predominantly due to the raw material, the 6082-T6 aluminum rotor experiences drastic cost reduction, with reasonable raw material and machining values, resulting in 93.5% savings. Finally, the PA6 rotor is the cheapest, with a value 97.7% lower than the original rotor, due to the low cost of the raw material and the machining process.

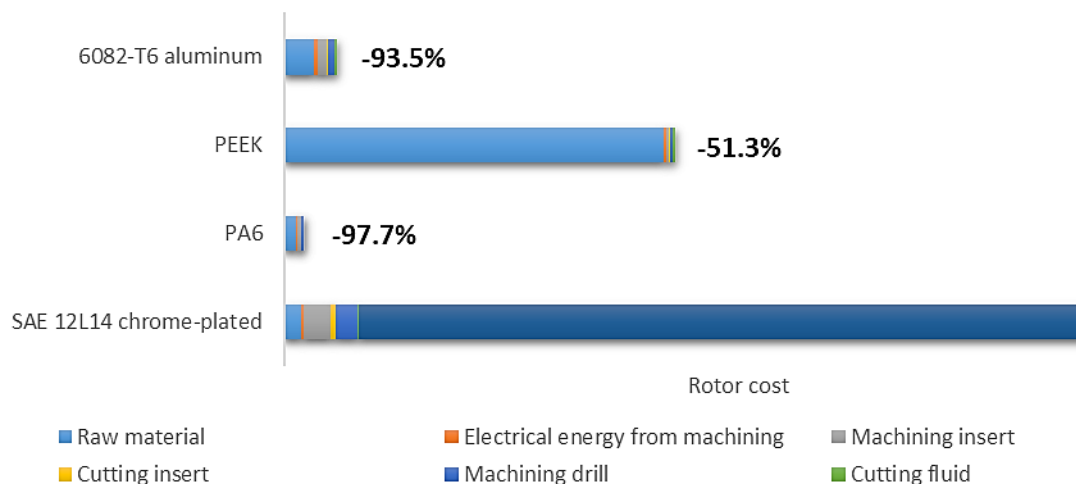


Figure 21. Rotor cost.

Qualitative comparison of results for different materials applied to the rotor

A qualitative summary of the results found is presented in Table 2 to illustrate a general overview of the work carried out and facilitate the comparison of performance and selection of the materials studied.

**Table 2.** Qualitative comparison of different materials applied to the PCP rotor. Each arrow indicates 25% of weighting

| Description  | SAE 12L14<br>chrome-<br>plated | PA6  | PEEK | 6082-T6<br>aluminum |
|--|--------------------------------|------|------|---------------------|
| Dimensional stability in the currently used machining process        | ↑                              | ↑↑↑  | ↑↑   | ↑↑↑↑                |
| Resistance to tinting colorant                                       | ↑↑↑↑                           | ↑↑   | ↑↑↑  | ↑↑↑↑                |
| Rotor wear (better performance)                                      | ↑↑↑↑                           | ↑    | ↑↑   | ↑↑↑                 |
| Stator wear (better performance)                                     | ↑                              | ↑↑↑↑ | ↑↑↑  | ↑↑                  |
| PCP characteristic curve (flow x pressure)                           | ↑↑↑                            | ↑    | ↑↑   | ↑↑↑↑                |
| PCP electrical consumption (better performance)                      | ↑↑↑                            | ↑    | ↑↑   | ↑↑↑↑                |
| Electrical consumption of the machining process (better performance) | ↑                              | ↑↑↑↑ | ↑↑↑  | ↑↑                  |
| Specific cutting and machining energy (better performance)           | ↑↑                             | ↑↑↑↑ | ↑↑↑  | ↑↑↑                 |
| PCP volumetric and global efficiency                                 | ↑↑↑                            | ↑    | ↑↑   | ↑↑↑↑                |
| Environmental impact (better performance)                            | ↑↑↑                            | ↑↑↑↑ | ↑↑   | ↑                   |
| Total cost (better performance)                                      | ↑                              | ↑↑↑↑ | ↑↑   | ↑↑↑↑                |
| Approximate qualitative average (best solution)                      | ↑↑                             | ↑↑↑  | ↑↑   | ↑↑↑↑                |

## Conclusion

The four materials studied for the rotor, although with very different mechanical properties, were approved from the point of view of durability in the application scenario of the tinting industry without presenting a failure of functional unfeasibility of the equipment at the end of the testing period. Furthermore, no significant wear was identified on the stator-rotor pairs, showing that the minimum lifetime does not challenge the integrity of the components. The machining process presents greater power and energy consumption for SAE 12L14 due to the superior mechanical properties that reproduce greater cutting force. The same behavior occurs for the specific energy of whirling and machining, which registers a higher value for this material and a lower value for PA6. Therefore, the PA6 rotor has lower electrical energy consumption for manufacturing.

For the energy efficiency of *PCPs*, the 6082-T6 aluminum rotor is the best material, translating into electrical energy savings and better flow and pressure performance produced in the pump. While the PA6 rotor is considered less energy efficient for the pump, the use of the cleaner production methodology showed that the best environmental solution among the four materials studied is the PA6 rotor, because it is the only one capable of dry machining, eliminating problems with the cutting-edge fluid.

Rotor costs reach completely different levels. The PEEK rotor records a 51.3% reduction in final value, the 6082-T6 aluminum rotors 93.5%, and the PA6 an impressive 97.7% reduction. In general, it was concluded that the best performance and energy efficiency solution for the pump is the 6082-T6 aluminum rotor. However, for the energy efficiency of the manufacturing process, environmental impact, and cost, it is the PA6 rotor. As Wear was not a limitation to the use of any of the proposed materials, based on the small difference in cost between 6082-T6 aluminum and PA6. It is concluded that the best alternative for the currently used rotor (SAE 12L14 chrome-plated) is a 6082-T6 aluminum rotor. As it represents a flow in the pump equal to or greater than the SAE 12L14 chrome-plated rotor, not having any significant impact on the use of the equipment, the use of PA6 rotors would reduce the productivity of the equipment in approximately 18%.

This work makes an unprecedented contribution because, until now, there were no studies on rotor wear on this type of pump in the tinting industry. Therefore, exploring alternative materials for this application, which are not materials with extremely high hardness and mechanical resistance, for the rotor of a PCP, proved to be possible and viable based on the evaluations. Furthermore, there were no studies on the application of Cleaner Production methodology for PCP rotors.

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