Optimizations of contour finish turning of nodular cast iron with uncoated grooved tool using design of experiments

Otimizações do torneamento de acabamento de contorno em ferro fundido nodular com ferramenta ranhurada sem revestimento, utilizando o planejamento de experimentos

Optimizaciones del torneado de acabado de contornos en fundición nodular con herramienta ranurada sin recubrimiento, mediante el diseño de experimentos

Submitted on: 4.18.2026| Accepted on: 4.24.2026
DOI: 10.54899/rpd.v17n2-2699

Lúcio Albino Amaro da Silva
Master in Mechanical Engineering, E-mail: lucio.albino@ufrgs.br

Lírio Schaeffer
PhD in Mechanical Engineering, E-mail: 00002781@ufrgs.br

ABSTRACT

This work presents a case of study where tool life performance of a cemented carbide blank, class K-10 uncoated, had been significantly improved by the results of a Design of Experiments. This tool is used in a contour finish turning of Nodular cast iron. This material is largely used by manufacturing industry due to superior results in toughness and ductility. However its machinability is reported to be poorer than grey cast iron. When the manufacturing process request a grooved tool with a reduced angle, which was the problem in this case, tool life performance becomes critical as it is reported in this study. A Design of Experiments was performed with 2 levels and 3 factors and resulted in parameters that optimize the machining condition. These factors are the main variables of this process, which are: radial feed, axial feed and piece rotation. The result of the Design of Experiment tests achieved a tool life 157% higher than the previous condition empirically developed by the company owner of this process.

Keywords: Contour Turning; Uncoated Grooved Tool; Nodular Cast Iron; Design of Experiments.

RESUMO

Este trabalho apresenta um estudo de caso no qual o desempenho da vida útil de uma ferramenta de metal duro (carboneto cimentado), classe K-10 sem revestimento, foi significativamente aprimorado com base nos resultados de um Planejamento de Experimentos. Esta ferramenta é utilizada na operação de torneamento de acabamento de contorno em ferro fundido nodular. Esse material é amplamente empregado na indústria manufatureira devido aos seus resultados superiores em tenacidade e ductilidade. No entanto, relata-se que sua usinabilidade é inferior à do ferro fundido cinzento. Quando o processo de fabricação exige uma ferramenta com canal e ângulo reduzido — o que constituía o problema neste caso —, o desempenho da vida útil da ferramenta torna-se crítico, conforme relatado neste estudo. Foi realizado um Planejamento de Experimentos com 2 níveis e 3 fatores, resultando em parâmetros que otimizam as condições de usinagem. Esses fatores correspondem às principais variáveis do processo, a saber: avanço radial, avanço axial e rotação da peça. O resultado dos testes do Planejamento de Experimentos demonstrou uma vida útil da ferramenta 157% superior àquela obtida na condição anterior, desenvolvida empiricamente pela empresa detentora do processo.

Palavras-chave: Torneamento de Contorno; Ferramenta com Canal Sem Revestimento; Ferro Fundido Nodular; Planejamento de Experimentos.

RESUMEN

Este trabajo presenta un estudio de caso en el que el rendimiento de la vida útil de una herramienta —un inserto de carburo cementado de clase K-10 sin recubrimiento— se mejoró significativamente gracias a los resultados de un Diseño de Experimentos. Esta herramienta se utiliza en el torneado de acabado de contornos en fundición nodular. Este material es ampliamente empleado en la industria manufacturera debido a sus resultados superiores en términos de tenacidad y ductilidad. Sin embargo, se reporta que su maquinabilidad es inferior a la de la fundición gris. Cuando el proceso de manufactura requiere una herramienta ranurada con un ángulo reducido —lo cual constituía el problema en este caso—, el rendimiento de la vida útil de la herramienta se vuelve crítico, tal como se expone en este estudio. Se llevó a cabo un Diseño de Experimentos con 2 niveles y 3 factores, el cual arrojó parámetros que optimizan las condiciones de mecanizado. Estos factores corresponden a las variables principales del proceso: avance radial, avance axial y velocidad de rotación de la pieza. Como resultado de las pruebas del Diseño de Experimentos, se logró una vida útil de la herramienta un 157 % superior a la obtenida bajo las condiciones previas, las cuales habían sido desarrolladas empíricamente por la empresa propietaria del proceso.

Palabras clave: Torneado de Contornos; Herramienta Ranurada Sin Recubrimiento; Fundición Nodular; Diseño de Experimentos.

INTRODUCTION

Contour finish turning in a metal piece is an operation performed when a mechanical component requires it due to its functional characteristics. Almost all industrial products have some curve surfaces to be machined that require consideration of the effective cutting conditions (Hagiwara, 2009). This paper proposes to improve the contour turning operation, when it is applied to manufacture compression piston rings with nodular cast iron as metal base. On this product, continuous technological advances had focused on reducing pollutant emissions and on increasing lifetime of internal combustion engines. This had lead manufacturers to improve proprieties of the metal base; to use coatings more resistant and with better tribological characteristics and also implement changes in the metal base profile.

When compared to grey cast iron, nodular or ductile cast iron has better proprieties as higher strength, wear resistance, fatigue resistance, toughness and ductility. Graphite flakes in grey cast iron act as stress raisers at the shear plane and thus facilitates cutting. In ductile iron, on the other hand, the graphite spheres are less effective than the flake graphite in weakening the material in the shear plane, and the flow zone material may sometimes be extremely ductile. This, together with inherently enhanced mechanical proprieties of nodular cast irons, results in poorer machinability than that observed in grey cast irons (Yigit et al., 2008).

Besides the material improvement, the metal base piston ring profile has passed in the last years from a flat face to a curvilinear face, so that, in the final product, only part of the metal base presents coating. This configuration reduces the time required for softening the engine and improves the retention of the lubricating oil. This helps to stop the oil from passing in excess to the combustion chamber and be burned. At the same time, leaves a thin film of oil on the cylinder wall, which reduces the friction of the ring against the cylinder (Valente, 2008).

The machining of the required profile on the metal base is performed in a mechanical turning machine with CNC. This kind of operation requires that tool geometry have a profile next to the profile or contour which is desired to be machined in the piece. Because of that it is impracticable to use a conventional tool. Beyond that, this special profile varies for each specific type of piston ring, according its dimensional characteristics. Considering this profile results in less quantity of cutting edge material in the tool, there is a significant reduction of its tool life when compared with longitudinal turning, for the same amount of material removed using a conventional catalog tool. Moreover, we can consider contour turning a relatively new process for such product. Thus, the machining parameters still have significant opportunities for improvement. The analysis and optimization of process parameters aiming to achieve a better performance in finish turning over a piece of nodular cast iron, is the main scope of this work.

Whereas a lower profile angle of the tool is favorable to reduce scrap in the subsequent steps of the process, there are more details about this on item 2.3, it also reduces the amount of material on the cutting edge. So, the great challenge of this study is to improve quality of the final product, using a tool with low angle, while achieving gains in productivity. In other words, reduce the angle of the tool profile and still achieve a greater number of pieces turned than the previous condition.

This kind of problem is a typical optimization process that fits for an experimental design method. As it is already known, its usage in a process development can result in products that are easier to manufacture, have enhanced field performance, reliability and lower cost (Montgomery, 2005). So, design of experiments (DOE) provides a cost-effective means for solving problems and developing new processes. The simplest, but most powerful, DOE is the two-level factorial design. Each input variable is varied at high and low levels and the output observed for resultant changes. Statistics can then help determine which inputs have the greatest effect on outputs. One-factor-at-a-time (OFAT) experimentation will never reveal interactions between factors. Two-level factorials are much more efficient than OFAT because they make use of multivariate design. It's simply a matter of parallel processing (factorial design) versus serial processing (OFAT) (Anderson and Kraber, 1999).

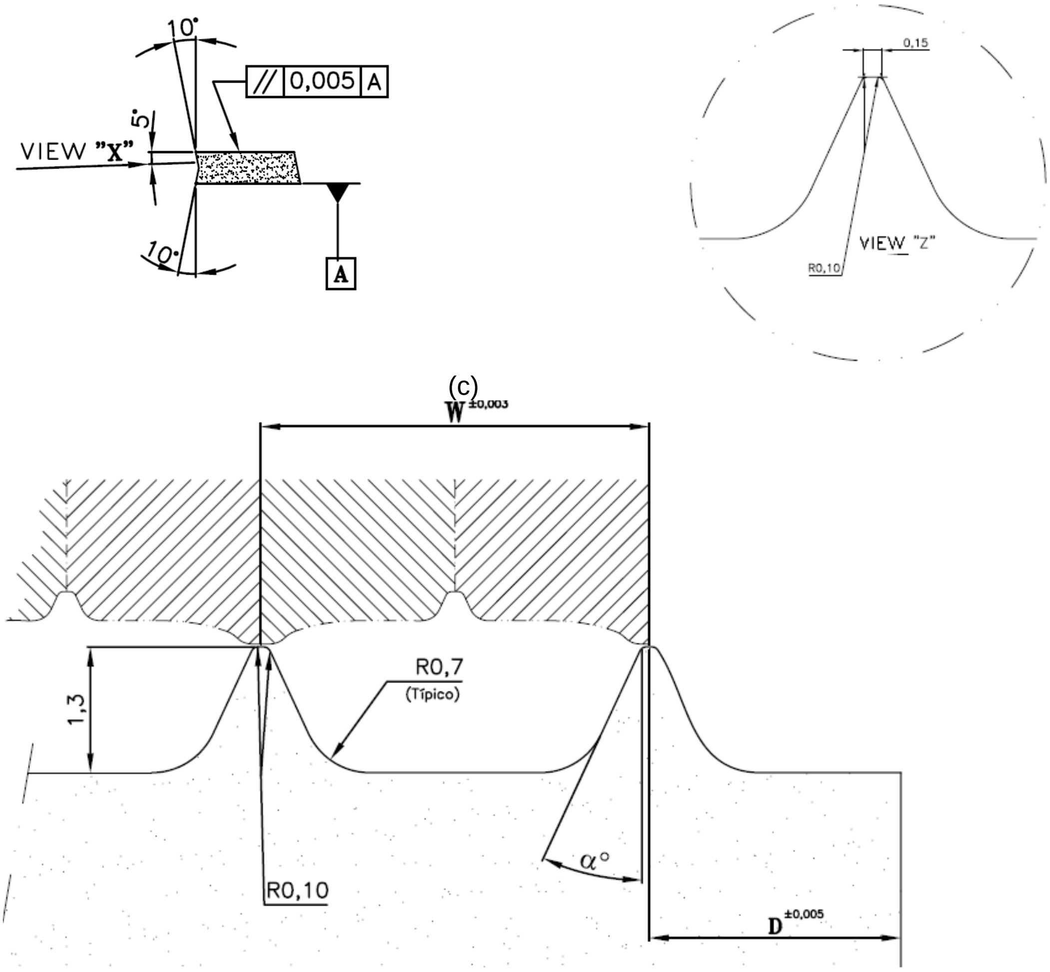
In this case study, a two level factorial with three factors is applied to screen these factors in order to identify those that significantly affect the response. The factors are the main variables of the process: radial feed, axial feed and piece rotation. After running and analyzing the experiments on Minitab software the responses showed the best parameters for these factors which lead the process to a performance 157% higher than the previous condition empirically developed by the company owner of this process.

EXPERIMENTAL DETAILS

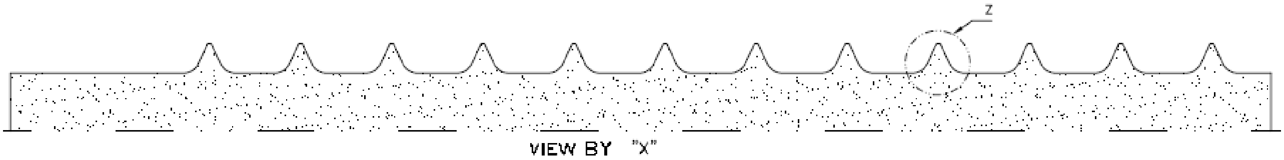
Uncoated Grooved Tool

The material of the tool is cemented carbide class K-10. The norm ISO 513 (2004a) defines this class with WC + Co in its composition, with high wear resistance, indicated for finish turning in materials with short chips such as cast iron and hardened steel. The average hardness of 5 readings in one tool is 79.3 HRC. The tool profile is shown in Fig. 1. The blank received from different suppliers is ground by Mahle to get the final grooved shape. As a result, the roughness of the upper face gets Ra ranging from 0.2 to 0.5 µm. In the initial condition of the process studied the angle (α), shown in Fig. 1 (b) is 30º and it was changed to 20º in order to get qualitative gains in subsequent operations of the process.

Figure 1. Groove tool drawings: (a) Side view; (b) Front view detail;
(c) Front view detail with piece machined hachured and (d) General front view.



(a) (b) (c) (d)



Source: Prepared by the autor.

Workpiece Caracterization

Workpiece Material

The workpiece material is nodular cast iron with high content of Niobium, very similar to material ISO 6621-3 (2004b), subclass 56. Its chemical composition is showed in Tab. 1. The higher content of alloying, which promotes microstructure having special properties, makes it a special cast iron with properties close to hardened steel. In this way, machinability is similar to steel and much worse than grey cast iron. The average hardness of 3 rings at 3 points each ring is 41.0 HRC. This ductile iron has tensile strength and modulus of elasticity, respectively at minimum of 1.300 MPa and 145.000 MPa.

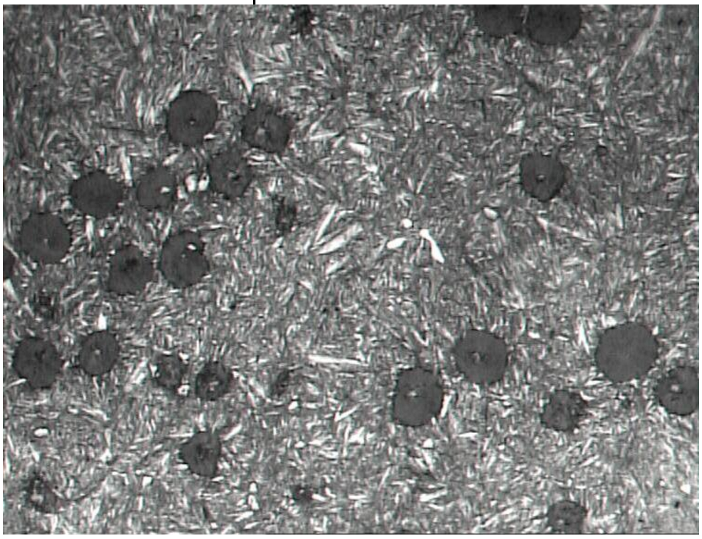
Table 1. Chemical composition of nodular cast iron with Niobium.

Element	C	Si	Mn	P	S	Ni	Mo	Mg	Nb
Amount (%)	3.5 – 4.1	2.4 – 2.9	0.2 – 0.8	max 0.15	max 0.03	max 0.7	max 0.3	0.02 – 0.07	0.4 – 0.6

Source: Mahle Catalogue, 2007.

Metallographic microscope picture of the material, with a microscope Leica DM IRM, is presented in Fig. 2. Microstructure consists of graphite nodules uniformly distributed with a small quantity of semi-spheroidal graphite. Matrix is tempered martensite without free ferrite and with isolated carbide particles uniformly distributed with less than 5%.

Figure 2. Graphite nodules in a tempered martensitic matrix etched with nital 3%, 500:1.

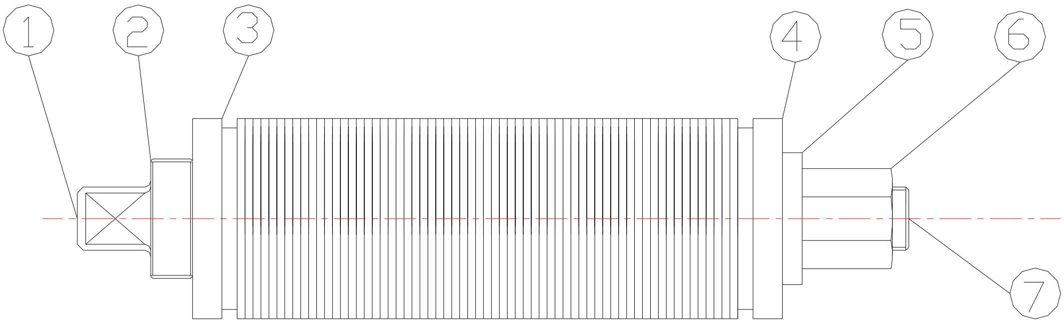


Source: Prepared by the autor.

Workpiece Dimensions

In this case study, the product machined is a piston ring. In order to machining it a quantity of pieces is assembled together in one arbor, resulting in a round bar of 380 mm in length, 75.75 mm in initial diameter and the total length, fixtures more work pieces, of 500 mm. Figure 3 shows an assembled arbor ready to be machined. The name of fixture parts are the follow: 1) Hand center on drag side; 2) Arbor; 3) Collar; 4) Spacer ring; 5) Washer; 6) Nut and 7) Hand center on nut side.

Figure 3. Overview of the arbor assembled ready to be machined.



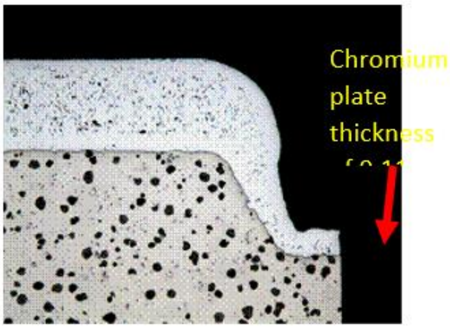
Source: Prepared by the autor.

New Tool Profile Angle

The justification to reduce the tool profile angle (α), shown in Fig. 1 (b), from 30º to 20º, is to reduce the chromium plate thickness in the bottom of the chamfer. In the process flow of the piston ring, after contour finish turning operation there is a coating process for deposition of chromium plate. Once it is done, unscrewing the nut indicated at number 6 in Fig. 3 opens the arbor. A lower chromium plate thickness in the bottom of the chamfer is desirable because it promotes the appearing and spread of linear crack fracture, facilitating the breaking of the layer in the opening of the arbor. If the chromium plate in that point is higher there is no more fragile point to shear. When the arbor is open, the breaking of the chromium layer between the rings occurs preferentially tear and not by pure shear, with crack surfaces displacement parallel to themselves and not to preferential perpendicular, generated by shear. Thus, a significant amount of chipping in the chromium plate is expected.

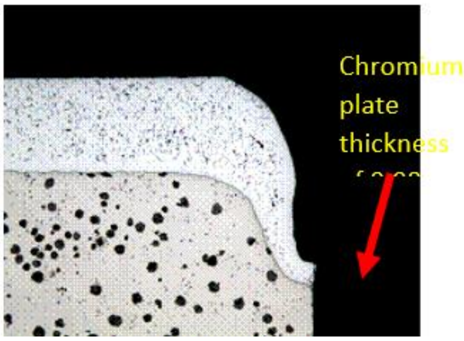
As can be seen in Figs. 4 and 5, using a tool with 20º angle results in less quantity of chromium deposition and as consequence a lower chromium thickness. Figure 4 show that when it is used a tool with 30º angle it is expected a chromium thickness of 0.11 mm in the bottom of the chamfer. On the other hand, a chromium thickness of 0.08 mm is expected when it is used a tool with 20º angle. The consequence in the product is a considerable reducing in the scrap by chips in the contact face of the piston ring. Using tool with 20º angle the chamfer gap is lower than a 30º angle. In Fig. 6 this chamfer gap is indicated as 0.625 mm, as a result of the use of a 30º angle in the tool. Once is used a 20º angle in the tool, this chamfer gap is only 0.385 mm, as indicated in Fig. 7. With a reduced area in the gap of the chamfer, during the plating deposition process the chromium can not reach the bottom as easy as it does with a large gap in the chamfer. A more difficult deposition clearly results in a lower chromium thickness in the bottom of the chamfer.

Figure 4. Cut view of a piston ring machined using tool with 30o profile angle.



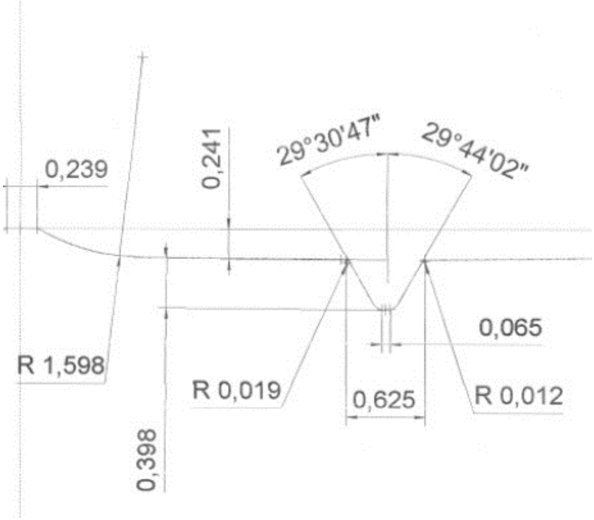
Source: Prepared by the autor.

Figure 5. Cut view of a piston ring machined using tool with 20o profile angle.



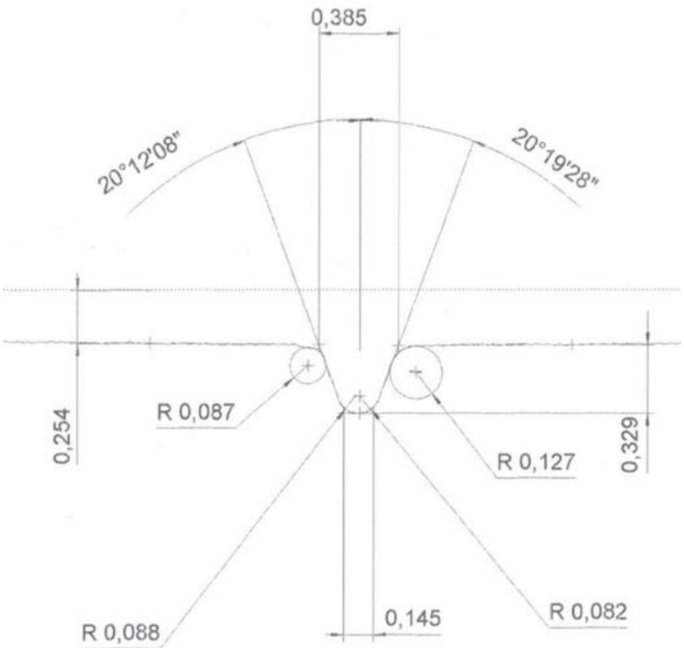
Source: Prepared by the autor.

Figure 6. Profile dimensions using a 30o angle in the tool.



Source: Prepared by the autor.

Figure 7. Profile dimensions using a 20o angle in the tool.

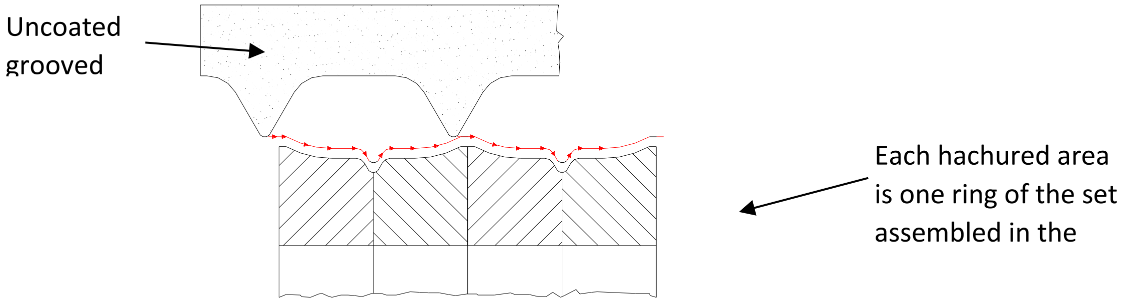


Source: Prepared by the autor.

Machining Process

The turning machine is a machine built by Mahle where a CNC Siemens 810D electronic controls one spindle tri-phases asynchronous engine with 11 KW, 9000 RPM, two axles, 6 Nm, 3000 RPM. This process runs with coolant, a diluted Plantocool MH 2002 6% in water supplied by Fuchs. It has no mineral oil in the composition and the addictives promote an excellent lubricant. It is indicated for severe machine applications (Fuchs Catalogue, 1997). The stock removal material is 0.25 mm. It is not only a longitudinal turning. To perform the contour requirement there is axial and radial movement. As shown in Fig. 8 the grooved tool moves along a part of the arbor with a radial feed removing material from diameter and in an axial feed removing material in the longitudinal movement.

Figure 8. Movement of the grooved tool while performs turning operation.



Source: Prepared by the autor.

End of Tool Life Criterion

The total number of turned arbors, with one sharpening, defines the lifetime of one grooved tool. The surface roughness expected in this kind of operation is around 1.0 µm Ra. The equipment available at Mahle to measure roughness is a Perthometer PRK PURV3-100. Unfortunately, it cannot follow the contour of the piece. So, it is not feasible to perform this kind of measurement at the shop floor. Because of this, in this case is adopted catastrophic failure as the tool life criterion. The catastrophic failure is deemed to have occurred when the tool wear is so large that the tool cannot do any cutting successfully. The cutting edge of the tool breaks off or vibration and noise gets loud. Beside of this, visual surface quality of every piece after turning is analyzed: scratches, burrs, trepidation, marks or flaws on the contour are not allowed.

Design of Experiments Planning

To achieve the results proposed for this study, it was chosen a two-level factorial design, a full factorial with replication, which results in 16 runs. Experience during this study has indicated three factors that have critical influence in this process. These factors been selected and are: radial feed, axial feed and piece rotation. It was decided one replicate in order to have a more precise estimate response. Replication improves the chance of detecting a statistically significant effect in the midst of natural process variation (Anderson and Kraber, 1999).

Before defining the two levels for each factor a set of experiments were run in order to choose those parameters that will save time on the experiments. With this procedure some information learned in one experiment can be applied to the next. It leads the authors to decrease rotation in 10% for DOE runs. Adding this information with the process experience it was decided also to increase axial and radial feed. After these considerations, levels get the values indicated on Tab. 2 and a DOE plan was created.

Table 2. Two levels and three factors defined for the experiments.

	Level 1	Level 2
Radial feed (mm/min)	6.3	7.2
Axial feed (mm/min)	12	15
Rotation (RPM)	180	190

Source: Prepared by the autor.

RESULTS AND DISCUSSION

Initial Condition

The parameters empirically developed by Mahle for this process was 4.0 mm/min for radial speed, 12.0 mm/min for axial speed and 211 RPM for piece rotation. The process output using these parameters is shown in Tab. 3. Cost per piece means the cost of one new tool divided by the total number of pieces produced with this tool.

Table 3. Results obtained with parameters used before this study.

Tool cutting angle	Arbors turned	Cost per piece (R$)	Cycle time (min)
30º	30	0,00368	12.5
25º	24	0,00460	
20º	14	0,00789	

Source: Prepared by the autor.

DOE Results

Table 4. DOE detailed description of runs and results.

	Parameters			Responses	
Run Order	Radial feed (mm/min)	Axial feed (mm/min)	Rotation (RPM)	Quantity of arbors	Cycle time (min)
1	7.2	12	180	43	12.80
2	6.3	15	190	20	11.30
3	6.3	12	180	22	13.25
4	7.2	15	190	28	10.82
5	6.3	12	190	26	13.25
6	7.2	15	180	32	10.82
7	7.2	12	190	29	12.80
8	6.3	15	180	26	11.30
9	7.2	12	190	24	12.80

10	7.2	15	180	34	10.82
11	7.2	12	180	37	12.80
12	6.3	15	180	32	11.30
13	6.3	15	190	11	11.30
14	6.3	12	180	23	13.25
15	6.3	12	190	30	13.25
16	7.2	15	190	25	10.82

Source: Prepared by the autor.

The experiments run in a randomized order as is indicated in Tab. 4. The responses selected were quantity of arbors and cycle time. The first one defines the tool life and the second one informs how much the productivity of the operation is affected by one specific parameter. The responses collected after tests were input in the factorial design created in the Minitab software. Of course, each response is input in the line of respective parameter tested, as indicated in Tab. 4.

After run a factorial analyzes, Minitab generates the selected graphs defined by user. In Fig. 9, it is showed two Pareto charts that were selected to show graphically summarized information about the relative importance of the differences between the three factors and its interactions for each response. They are disposal in bars sorted from most significant to least significant. The length of each bar is proportional to the statistical significance of that effect. The first Pareto chart shows that tool life is greatly affected by radial feed, rotation and by interaction between the three factors. The vertical red line is the critical value line. It indicates that factors, presented in Fig. 9, over 2.306 value of standardized effect are significant, considering 5% of significance level (Polhemus, 2005). For this response, axial feed and other interactions have minor influence, as they are below to the left of the red line.

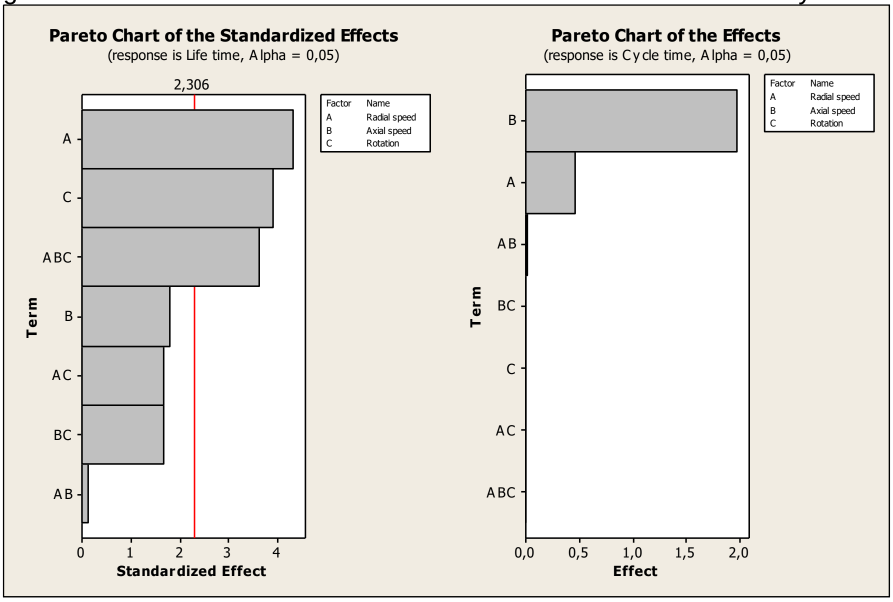
The other Pareto chart shows that cycle time is mainly affected by axial speed. As the longitudinal machining movement is much larger than radial movement, 380 mm in axial movement and only 0.25 mm in radial movement, this result is already expected. The red line is not showed because the standard error for effects is zero. From this chart it is clear that rotation and all interactions between the three factors have no effect in cycle time.

Table 5. Results obtained with parameters used before this study.

Radial feed (mm/min)	Rotation (RPM)	Machining time (sec)
6.3	190	7.5367
6.3	180	7.1400
7.2	190	6.5867
7.2	180	6.2400

Source: Prepared by the autor.

Figure 9. Pareto charts with factors that affect tool life time and total cycle time.

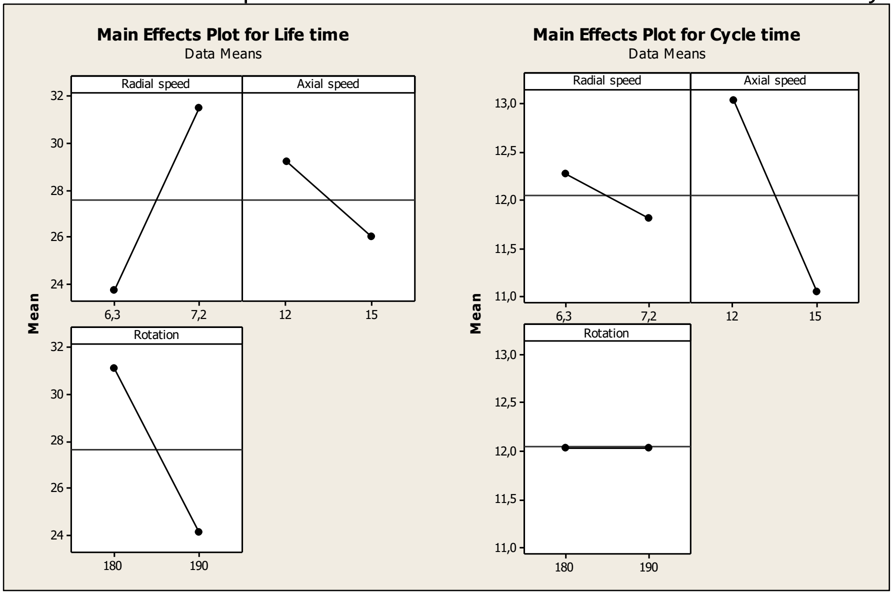


Source: Prepared by the autor.

The main effects for each factor are presented in Fig. 10. The reference line in these graphs represents the overall mean of the data and it helps the user to visualize the magnitudes of main effects. The first graph presents the results for tool life, which higher is better. It shows that a higher radial speed together with a lower rotation increases the lifetime of the tool. A decrease in axial speed has a minor effect but also can contributes to increase the lifetime. From that it is clear that the key factor to improve the tool life is machining time or the contact time between tool and piece while performing machining operation. Considering a radial movement of 0.25 mm, the machining time related only to radial movement is 2.38 seconds for radial feed of 6.3 mm/min and 2.08 seconds for radial feed of 7.2 mm/min. So, this higher radial feed results in a decrease of 12.5% in the time of contact between tool and piece. The machining time calculated for each pair of parameters is showed in Tab. 5. The set of parameters, which results in lower machining time, will increase the tool life of the grooved tool.

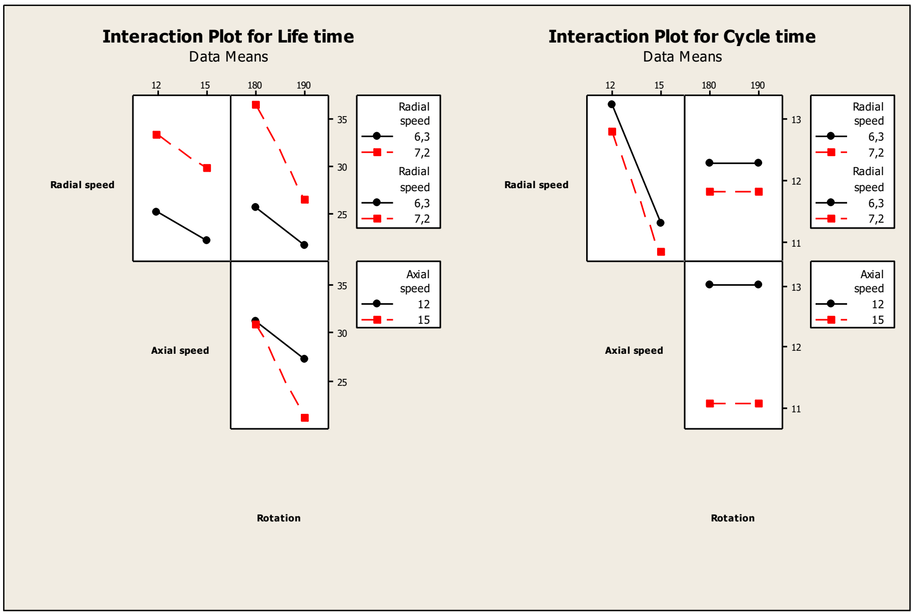
The second set of graphs presents the results for cycle time, which lower is better. In this graph, it is clear that axial speed has major influence on cycle time. As already discussed, any changes in this parameter will result in proportional changes on cycle time. The other two factors, radial speed and rotation have respectively minor and no influence on cycle time.

Figure 10. The main effects plot for each factor that affect tool life time and total cycle time.



Source: Prepared by the autor.

Figure 11. Interactions plot between factors, showing its influence in tool lifetime and total cycle time.



Source: Prepared by the autor.

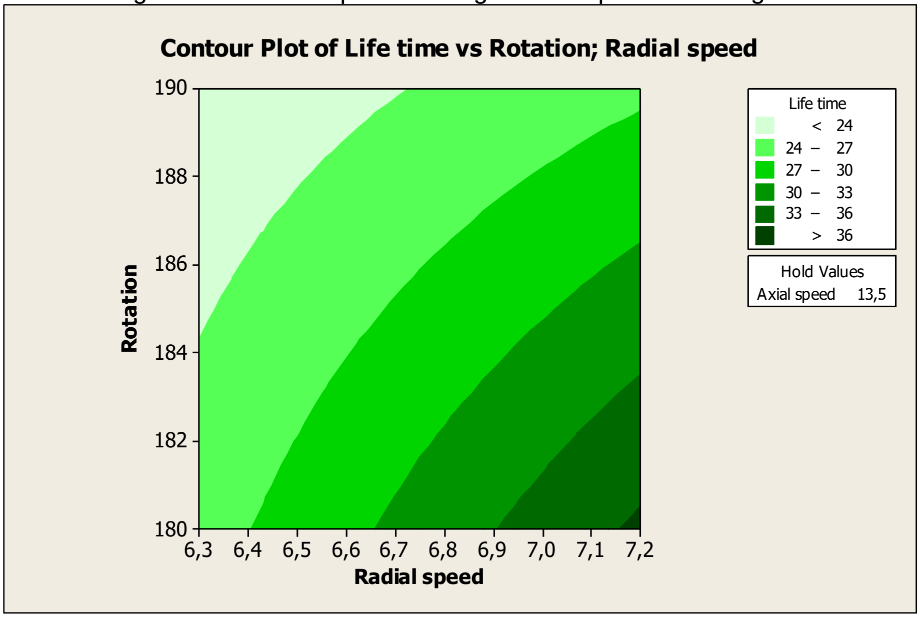
In Fig. 11 it is presented the interactions plot between the three factors, showing its influence in the responses. In this kind of graph parallel line indicates no influence. On the other hand, crossed lines or lines with different inclination indicate interaction between the correspondent factors. From that it is clear that lifetime is greatly affected by interaction between rotation and the two speeds, radial and axial, by the results in the first graph. The other interaction plot confirms that rotation has no influence on cycle time. Also, the parallel lines in the speeds interaction indicated that there is no interaction between then that affect the cycle time.

Another graph important to analyze is contour plot. It shows how response variables relate to two continuous design variables while holding the rest of the variables in a model at certain settings. In a contour plot, the fitted response model is viewed as a two-dimensional surface where all points that have the same fitted value are connected to produce contour lines of constants. Contour plots are useful for establishing operating conditions that produce desirable response values (Minitab, 2007). As already reported, life time of the tool is greatly affected by rotation and radial speed. So these are the factors choose to be analyzed in a contour plot, presented in Fig. 12. The darkest areas indicate the interpolation values for a best relationship between these two factors. So, the contour plot of tool life versus rotation and radial feed shows the best parameter region. It indicates the parameters values that optimize the responses.

These optimized parameters are better quantified in Fig. 13, where values indicated by Minitab Software are presented in a Desirability graph. The desirability function approach is one of the most widely used methods in industry for the optimization of multiple response processes. It is based on the idea that the "quality" of a product or process that has multiple quality characteristics, with one of them outside of some "desired" limits, is completely unacceptable. The method finds operating conditions, input factors that provide the "most desirable" response values (Nist/Sematech, 2006).

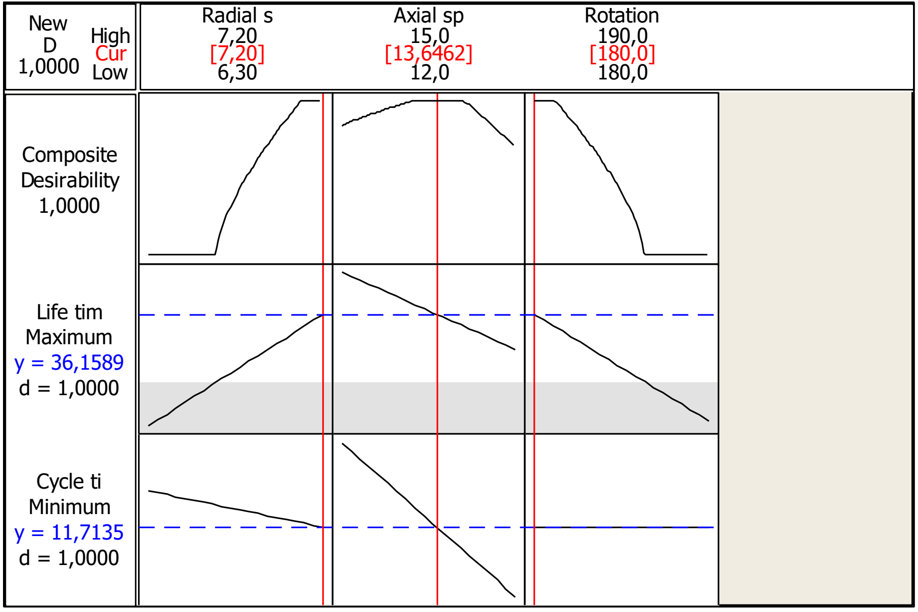
Minitab software uses this Desirability function to identify the combination of input variable settings that jointly optimize a single response or a set of responses. Joint optimization must satisfy the requirements for all the responses in the set. The overall desirability (D) is a measure of how well you have satisfied the combined goals for all the responses. Overall desirability has a range of zero to one. One represents the ideal case; zero indicates that one or more responses are outside their acceptable limits (Minitab, 2007).

Figure 12. Contour plot showing the best parameter region.



Source: Prepared by the autor.

Figure 13. Results obtained by Minitab Software showing the optimized parameters.



Source: Prepared by the autor.

Table 6. Results and gains observed after DOE study.

	Final results	Comparative with initial tests using angle 20º
Radial feed (mm/min)	7.2	
Axial feed (mm/min)	13.6	
Rotation (RPM)	180	
Quantity of arbors turned per sharpening	36	+157%
Cycle time (min)	11.7	-6,4%
Final cost per piece (R$)	0,0021	-73,4%

Source: Prepared by the autor.

The optimized parameters were implemented in the finish turning operation that uses an uncoated grooved tool. Results registered after the DOE studies were compared to the initial condition, as indicated in Tab. 6. As the initial quantity of arbors with one sharpening in finish turning operation that uses a grooved tool with angle 20 º was 14, the gain obtained with 36 arbors as final result is 157%. A reduction in cycle time from 12.5 minutes to 11.7 minutes represents a productivity increase of 6.4%. Also, when is considered the cost of one tool divided by the total number of arbors machined there was observed a reduction in the cost per piece from 0.00789 to 0.0021, expressed in Brazilian money (Real, R$).

CONCLUSIONS

From the results and discussion of the previous sections the main conclusions after applying a Design of Experiments with a goal to optimize a finish turning operation of nodular cast iron with uncoated grooved tool are:

1) An increase in radial speed together with a decrease in rotation has a great effect in lifetime of the tool. After the definition of new parameters an improvement in the quantity of arbors machined of 157% was achieved.
2) Cycle time of this finish turning operation is basically only affected by axial speed. With the new parameter a decrease of 6.4% in the cycle time was registered.
3) The improvements in the process were achieved even with a reduction in the tool angle from 30° to 20°.
4) Planning and executing a design of experiments to optimize a production process proves to be a feasible and effective way to improve process with low cost and precise results. A two factorial with replication was performed and the results lead to the best solutions for each response.

REFERENCES

ANDERSON, M.J.; KRABER, S.L. **Eight Keys to Successful DOE**. Quality Digest. Available: *http://www.qualitydigest.com/july99/html/doe.html*. July, 1999.

FUCHS CATALOGUE. **Technical Informations: Plantocool MH2002**. Brazil, 1997.

HAGIWARA, H. et al. **Contour finish turning operations with coated grooved tools: Optimization of machining performance**. Journal of Materials Processing Technology, Vol. 209, pp. 332-342, 2009.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. **Classification and application of hard cutting materials for metal removal with defined cutting edges – Designation of the main groups and groups of application**. Norm ISO 513, 2004.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. **Classification and application of hard cutting materials for metal removal with defined cutting edges – Designation of the main groups and groups of application**. Norm ISO 6621-3, MC 56, 2004.

MAHLE CATALOGUE. **Materials Piston Rings**. São Paulo, 60p. 2007.

MINITAB. **Guia do Usuário**. Belo Horizonte, 144p., 2007.

MONTGOMERY, D.C. **Design and Analysis of Experiments**. Ed. John Wiley & Sons, Arizona, United States of America, 641 p., 2005.

NIST/SEMATECH. **E-Handbook of Statistical Methods – Engineering Statistics Handbook**. Available: *http://www.itl.nist.gov/div898/handbook/html*, 2009.

POLHEMUS, N. **Statgraphics Centurion, How to guides**. Available: *http://www.statgraphics.com/How%20To%20Perform%20an%20Optimization%20Experiment.pdf*, 2005.

YIGIT, R. et al. **Effect of cutting speed on the performance of coated and uncoated cutting tools in nodular cast iron**. Journal of Materials Processing Technology, Vol. 204, pp. 80-88, 2008.

VALENTE, R. **Blog carburado. Anéis de pistão – 2a parte**. Available: *http://blogcarburado.blogspot.com/2008/09/os-anis-de-pisto-2-parte.html*, 2008.