# COB-2021-2253 - OPTIMIZATION DUPLEX STAINLESS STEEL UNS S32205 MILLING PROCESS USING CONTROL CHART

**Bárbara Salvador Barros da Silva**[1]
d2019010014@unifei.edu.br
**Gustavo Rocha Queiroz**[1]
gustavoqueiroz@unifei.edu.br
**Harue Genghini Shibuta**[1]
harueshibuta@unifei.edu.br
**Leonardo Albergaria Oliveira**[1]
leoalber@unifei.edu.br
**Tarcísio Gonçalves de Brito**[1]
tgbrito@unifei.edu.br
**Thaisy Emanuele Benicio**[1]
thaisyebenicio@unifei.edu.br

[1]IEI-UNIFEI-Universidade Federal de Itajubá. Campus Avançado de Itabira. Rua Irmã Ivone Drummond, nº 200. CEP:35903-087. Itabira-MG[1]

***Abstract.***

*Milling is one of the most used processes in metal machining because it allows high productivity and low cost. In this scenario, duplex stainless steels UNS S33205 have been gaining prominence for being cost-effective, although their low machinability influences the final product. In order to guarantee the surface quality of the machined parts, it is necessary to have planning and control of the cutting parameters in order to obtain the lowest values of roughness during the process. For this, Statistical Control becomes indispensable for monitoring the variables of the project. Aligned in these conditions, this paper aims to carry out a statistical analysis of the $R_a$ surface roughness to evaluate the quality of the machined surface in the end milling process of duplex stainless steel UNS S32205. Such analysis is performed using Control Charts and indices for Capability Analysis, seeking the best condition of the cutting speed and the amount of fluid as an input parameter. It was possible to verify moderate stability in the processes with speeds rate of 60 m/min, 65 m/min and 70 m/min both for the minimum flow. Despite obtaining points outside the lower control limit, these meant a gain in quality for the project. Only the process with a speed of 70 m/min was able to operate within the specified surface roughness limits of the part between 0.25 and 0.55 µm.*

***Keywords:*** *Capability analysis, Milling. Roughness, Control charts, duplex stainless steel UNS S32205.*

## 1. INTRODUCTION

End milling is one of the most widely used operations in the manufacturing industries often used in profiles, grooves, contours and pockets in the manufacture of equipment for oil and gas industries, offshore platforms, mechanical components and corrosion resistant parts manufactured in stainless steels (KALIDASS and PALANISAMY, 2014). In the milling of duplex stainless steels, the absence of the cutting fluid contributes to the increase of the heat generated in the tool-part interface, increasing the temperature located in the cutting region causes the adhesion of the material being machined in the cutting tool, leading to premature wear and decreasing the quality of the machined surface (Krolczyk, 2014; Rajaguru and Arunachalam, 2017).

These steels are difficult to machine because they have austenite and nitrogen contents, in addition to the low thermal conductivity that influences the surface quality of milling parts (Liu, *et* al., 2013; Selvaraj, 2017; Policena *et al.*, 2018). Surface roughness is one of the critical parameters that influence the quality of the machined part.

The roughness of a surface is defined as a set of fine irregularities or micrometric errors resulting from the action of material pullout and the cutting process (Grunner, 2018).

Quality has been discussed by several researchers to establish greater efficiency and lower cost, seeking better machine tool configuration, providing the development of various methodologies (Brito et al., 2014; Costa *et al.*, 2016; Costa *et al.*, 2017).

The Statistical Process Control (SPC) is a great ally when visualizing possible problems or variation of processes. The search for quality and increment of profits that take along some factors such as cost reduction and competitiveness can be facilitated by this way of work without losing product quality. The SPC tends to reduce or even eliminate rework and increase productivity as a result (Montgomery, 2016). Control charts are used to monitor the accuracy of measurement processes over time by using observed deviations known patters. According to Montgomery (2016), in order to the processes be considered under statistical control, the sampling points must be established within the control limits and they must be randomly varying around the center line. Points outside the limit show that the processes are out of control which requires corrective actions to eliminate the attributable causes responsible for the deviation.

This research aims to perform an analysis of surface roughness ($R_a$) based on the end milling of UNS S32205 stainless steel, using Control Charts and capability index for three cutting and cooling speeds under different conditions. The input parameters of this research are $R_a$, cutting speed ($v_c$), feed per tooth ($f_z$), radial depth of cut ($a_e$) and axial depth of cut ($a_p$) and for cooling are maximum flow, minimum flow and without fluid. The result obtained was the roughness stability for UNS S32205 stainless steel, quality of the machined surface ranging between 0.25 μm and 0.55 μm.

## 2. CONTROL CHARTS

The Control Chart stands out as the main element of Statistical Process Control (SPC), are graphs that present the measurement of a characteristic of a production lot as a function of the time or sample number that makes it possible to monitor the studied process, (Montgomery, 2013, Psarakis, 2015).

The construction of the Control Chart is carried out after the learning phase, in which the process is stable, and then it is possible to establish the average value of the quality analyzed in the measurement, and the upper and lower limits, which correspond to the acceptable deviations to consider the process under control (Montgomery, 2013).

According to Montgomery (2013) the control charts for variables that is the most commonly used to inspect an independent variable are the control charts X and $\overline{R}$ mean and amplitude, respectively. The limits for the e graphs X and $\overline{R}$ are given according to the following equations (1 to 6).

$$LSC_X = \bar{\bar{x}} + \frac{3}{d_2\sqrt{n}}\bar{r} \tag{1}$$

$$LSC_X = \bar{\bar{x}} - \frac{3}{d_2\sqrt{n}}\bar{r} \tag{2}$$

$$LC_X = \bar{x} \tag{3}$$

$$LSC_R = \bar{r} + \frac{3\,d_3}{d_2\sqrt{n}}\,\bar{r} \tag{4}$$

$$LIC_R = \bar{r} - \frac{3\,d_3}{d_2\sqrt{n}}\,\bar{r} \tag{5}$$

$$LC_R = \bar{r} \tag{6}$$

The procedure for constructing control charts involves sampling fixed sizes at sample intervals. Through these samples, the average, dispersion and specific limits of the process are calculated. In order to build a control chart, samples of fixed size **n** must be extracted from the process to be analyzed, which may or may not have the same periodicity, which usually depends on sample availability, collection difficulty or even cost (Montgomery, 2013).

$\overline{R}$ is the average of the amplitudes of all samples collected and $d_2$ and $d_3$ are constants that depend on the sample size.

According to Montgomery (2013), in order for the process to be considered under statistical control, the sampling points must be within the control limits, in addition to varying randomly around the center line. Points outside the limit show that the process is out of control, requiring corrective actions to eliminate the attributable causes responsible for the deviation.

The control chart is an extremely useful tool to identify whether the variations observed in a process are due to common causes of variation, or arising from special causes of variation, which need to be identified and eliminated from the processes according to Linna and Woodall (2001).

## 3. PROCESS CAPABILITY ANALYSIS

Statistical Process Control (SPC) is one of the main methodologies applied in production lines with the objective of reducing variability, providing an increase in quality and cost reduction minimizing tailings and rework. The reduction of variability contributes to the improvement of product performance, increasing the competitive capacity of the company (MONTGOMERY, 2013).

Capability Analysis is a tool that uses indexes to quantify the variability of a process according to Montgomery (2016). Capability Analysis is measured by variability of a stable process in relation to project specifications. The commonly used capability indexes are the $C_p$ and $C_{pk}$. The potential capability index of the process ($C_p$), considers that the process is centered on the nominal value of the specification and relates the variability specified to the process with its natural variability, according to Equation 7.

$$C_p = \frac{LSE-LIE}{6\sigma} \qquad (7)$$

Where LSE and LIE are the upper and lower limits of specification, respectively, and is the standard deviation ($\sigma$).

The index takes into account the distance of the process mean in relation to the specification limits and can be calculated according to Equation 8:

$$C_{pk} = \min\{\frac{\mathrm{LSE} - \bar{\mathrm{X}}}{3\sigma}; \frac{\mathrm{LIE} - \bar{\mathrm{X}}}{3\sigma}\} \qquad (8)$$

If the values of $C_p$ and $C_{pk}$ are less than 1, the process is considered incapable. If the values are between 1 and 1.33 the process is considered relatively capable, and if the values are greater than 1.33 the process is potentially capable. The advantage of using these indices is that they are dimensional, facilitating the comparison of production processes, regardless of what is being produced (Montgomery, 2016).

A process is considered capable in relation to a given characteristic if its natural variability is less than the amplitude of the specification limits. Control limits monitor the existence of special causes and the statistical control condition of the process, while specification limits monitor the process's ability to meet project requirements.

## 4. EXPERIMENTAL PROCEDURE

The experiments were carried out in a CNC machining center of the Eurostec brand, with power of 15kW and maximum spindle rotation of 10.000 rpm. The tool used in this research was constituted by a top cutter code R390-025A25-11M, with diameter of 25mm, position angle kr = 90º, cylindrical rod, medium pitch with 3 inserts and mechanical fixation by clamp. The inserts were hard metal ISO M30, code R390-11 T3 08M-MM 2030 (Sandvik-Coromant 2018), coated with (Ti,Al)N +TiN by the physical vapor deposition process (PVD), according to Figure 1. The material used in the milling process was UNS S32205 duplex stainless steel and chemical composition according to Table 1, with 115x115x170 mm long and average hardness of 250 HB. The production specifications were determined for $R_a$ surface roughness between 0.25 to 0.55 μm, specified for the limits of the control chart. For the end of the tool life, the criterion of flank wear of $v_{bmax}$ = 0.30 mm was adopted.

Figure 1. Cutting tool used

Table 1. Chemical composition of duplex stainless steel UNS S32205.

| Al | C | Co | Cr | Cu | Mn | Mo | N | Ni | P | S | W |
|---|---|---|---|---|---|---|---|---|---|---|---|

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.008 | 0.013 | 0.05 | 22.24 | 0.19 | 1.22 | 3.14 | 0.19 | 5.62 | 0.019 | 0.01 | 0.02 |

The machining conditions used in the experiments were without fluid, with fluid at minimum flow (150 ml/min) and with fluid at maximum flow (12 l/min), using the Quimatic MEI synthetic oil with 5% concentration. The experiments were performed with cutting speeds ($v_c$) 60, 65 and 70 m/min, the cutting parameters used were feed per tooth ($f_z$) = 0.10 mm/tooth, cutting depth ($a_p$) fixed at 1.00 mm and radial depth of cut ($a_e$) = 17.50 mm, as show in table 2.

Table 2. Process parameters used in the milling process.

| Cutting Spade ($v_c$) [m/min] | Cutting fluid flow rate (Q) | | | $a_e$ [mm] | $a_p$ [mm] | $f_z$ [mm/tooth] |
|---|---|---|---|---|---|---|
| | Fluid-free condition | minimum flow | maximum flow | | | |
| 60 | 0 | 150 ml/min | 12 l/min | | | |
| 65 | 0 | 150 ml/min | 12 l/min | 17.50 | 1.00 | 0.10 |
| 70 | 0 | 150 ml/min | 12 l/min | | | |

The surface roughness values ($R_a$) were measured with a portable surface roughness tester Mitutoyo Surface SJ-201 M/P according Figure 2, using a 0.8 mm cut-off. The values were measured in three points of the work piece, one at the center and the other at each end, in order to consider the mean value of the readings and according to tables 3, 4 and 5.

The number of trials equals the flank wear condition adopted of $v_{bmax}$ = 0.30 mm for the tool. It can be observed that the fluid flow interferes with the wear for each cutting condition. The number of trials decreases as the cutting speed increases.

Figure 2 – Portable roughness meter used in the experiment.

Table 3. Ra (µm) values obtained in the experiment with $v_c$ = 60 m/min

| N° Experiment | Maximum Cutting fluid (Q) [l/min] | | | Minimum Cutting fluid (Q) [ml/min] | | | Without cutting fluid (Q) [l/min] | | |
|---|---|---|---|---|---|---|---|---|---|
| | $R_{a1}$ | $R_{a2}$ | $R_{a3}$ | $R_{a1}$ | $R_{a2}$ | $R_{a3}$ | $R_{a1}$ | $R_{a2}$ | $R_{a3}$ |
| 1 | 0.418 | 0.378 | 0.396 | 0.314 | 0.293 | 0.388 | 0.378 | 0.597 | 0.511 |
| 2 | 0.304 | 0.399 | 0.513 | 0.308 | 0.281 | 0.294 | 0.507 | 0.425 | 0.473 |
| 3 | 0.656 | 0.677 | 0.82 | 0.239 | 0.288 | 0.307 | 0.732 | 0.804 | 1.275 |
| 4 | 0.693 | 0.751 | 0.676 | 0.328 | 0.415 | 0.45 | | | |
| 5 | 0.39 | 0.234 | 0.261 | 0.416 | 0.513 | 0.342 | | | |
| 6 | 0.428 | 0.298 | 0.319 | 0.421 | 0.406 | 0.399 | | | |
| 7 | 0.524 | 0.621 | 0.657 | 0.415 | 0.432 | 0.43 | | | |
| 8 | 0.421 | 0.453 | 0.412 | 0.631 | 0.558 | 0.618 | | | |
| 9 | 0.621 | 0.538 | 0.563 | 0.694 | 0.742 | 0.755 | | | |
| 10 | 0.514 | 0.393 | 0.417 | 0.699 | 0.661 | 0.623 | | | |
| 11 | 0.608 | 0.764 | 0.757 | 0.513 | 0.374 | 0.432 | | | |
| 12 | 0.677 | 0.577 | 0.603 | 0.423 | 0.605 | 0.743 | | | |
| 13 | 0.678 | 0.697 | 0.693 | | | | | | |

Table 4. Values of Ra (μm) obtained in the experiment with $v_c$ = 65 m/min

| N° Experiment | Maximum Cutting fluid (Q) [l/min] | | | Minimum Cutting fluid (Q) [ml/min] | | | Without cutting fluid (Q) [l/min] | | |
|---|---|---|---|---|---|---|---|---|---|
| | $R_{a1}$ | $R_{a2}$ | $R_{a3}$ | $R_{a1}$ | $R_{a2}$ | $R_{a3}$ | $R_{a1}$ | $R_{a2}$ | $R_{a3}$ |
| 1 | 0.327 | 0.261 | 0.346 | 0.304 | 0.264 | 0.272 | 0.675 | 0.71 | 0.854 |
| 2 | 0.333 | 0.457 | 0.255 | 0.315 | 0.24 | 0.267 | 0.763 | 0.755 | 0.773 |
| 3 | 0.474 | 0.352 | 0.27 | 0.238 | 0.285 | 0.348 | 0.829 | 0.789 | 0.796 |
| 4 | 0.403 | 0.478 | 0.471 | 0.276 | 0.311 | 0.301 | | | |
| 5 | 0.555 | 0.331 | 0.354 | 0.282 | 0.299 | 0.459 | | | |
| 6 | 0.411 | 0.313 | 0.423 | 0.416 | 0.535 | 0.576 | | | |
| 7 | 0.272 | 0.207 | 0.193 | 0.637 | 0.42 | 0.622 | | | |
| 8 | 0.232 | 0.303 | 0.252 | 0.513 | 0.51 | 0.795 | | | |
| 9 | 0.33 | 0.329 | 0.403 | | | | | | |
| 10 | 0.48 | 0.481 | 0.512 | | | | | | |
| 11 | 0.483 | 0.479 | 0.631 | | | | | | |
| 12 | 0.593 | 0.551 | 0.658 | | | | | | |

Table 5. Values of Ra (μm) obtained in the experiment with $v_c$ = 70 m/min.

| N° Experiment | Maximum Cutting fluid (Q) [l/min] | | | Minimum Cutting fluid (Q) [ml/min] | | | Without cutting fluid (Q) [l/min] | | |
|---|---|---|---|---|---|---|---|---|---|
| | $R_{a1}$ | $R_{a2}$ | $R_{a3}$ | $R_{a1}$ | $R_{a2}$ | $R_{a3}$ | $R_{a1}$ | $R_{a2}$ | $R_{a3}$ |
| 1 | 0.335 | 0.292 | 0.322 | 0.221 | 0.352 | 0.357 | 0.712 | 0.631 | 0.587 |
| 2 | 0.449 | 0.414 | 0.407 | 0.289 | 0.318 | 0.331 | 0.621 | 0.61 | 0.628 |
| 3 | 0.393 | 0.409 | 0.454 | 0.35 | 0.326 | 0.395 | 0.616 | 0.584 | 0.548 |
| 4 | 0.372 | 0.348 | 0.407 | 0.444 | 0.406 | 0.395 | | | |
| 5 | 0.521 | 0.513 | 0.498 | 0.531 | 0.529 | 0.366 | | | |
| 6 | 0.294 | 0.275 | 0.285 | 0.485 | 0.552 | 0.677 | | | |
| 7 | 0.315 | 0.365 | 0.371 | | | | | | |

## 5. RESULTS AND DISCUSSIONS

The surface roughness measurements showed a biased behavior in order to increase the values with each new measurement. This behavior can be explained by the wear of the tool that influenced the quality of the machined surface. UNS S32205 duplex stainless steel has low machinability due to the mechanical characteristics of material, which causes premature tool wear.

It can be observed that at maximum flow obtained higher yields in terms of passes and minimum flow better roughness in their respective cutting conditions. The points that are below the lower limit of control translates value less than 0.25 µm, from the manufacturing point of view this condition is ideal by itself to deal with quality of machined surface. The same does not happen for a condition without fluid that has no point below the specified limit.

This is due to the generation of heat during fluid-free machining, which increases the mechanical strength of the volume of material in the formation of the chip, decreasing its ductility in such a way that the adhesion of the chip to the worn cutting edge is facilitated. As soon as the cutting edge exits the workpiece in a revolution, it comes into contact with the air, which has a much smaller cooling capacity than the fluid.

Thus, the temperature of the material adhered to the tool does not decrease much, maintaining its high mechanical strength. In the interaction between cutting edge and piece in the next revolution, the material adhered to the cutting edge finds the material of the part with high strength due to high temperature, thus hindering the formation of the chip, and wearing the tool faster and decreasing the number of passes, with increased roughness of the surface. Among the tested conditions the minimum flow of fluid with of 65 m/min ($v_c$) showed better roughness behavior and a similar number of passes of the maximum flow rate with 60 m/min ($v_c$), until flank wear 0.30 mm adopted.

Based on the $R_a$ roughness means, control graphs were plotted for the duration and amplitude of the experiments using the Shewhart Control Charts, constructed with the aid of the Minitab software, according to figures (3 to 5), for the conditions of maximum flow (12 l/min), minimum flow (150 ml/min) rate and without fluid respectively. The process is not under statistical control for the roughness $R_a$, the plotted data does not randomly float within the control limits for the three cutting speeds. The samples are being displayed from three to three facilitate distribution on the control chart and are subdivided according to fluid flow.

Figure 3. Values of $R_a(\mu m)$ obtained in the experiment with $V_c = 60$ m/min

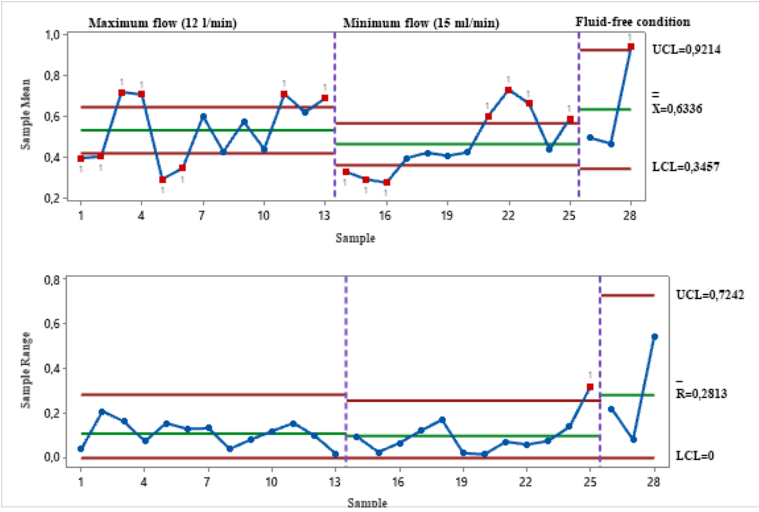



Figure 4. Values of $R_a(\mu m)$ obtained in the experiment with $V_c = 65$ m/min

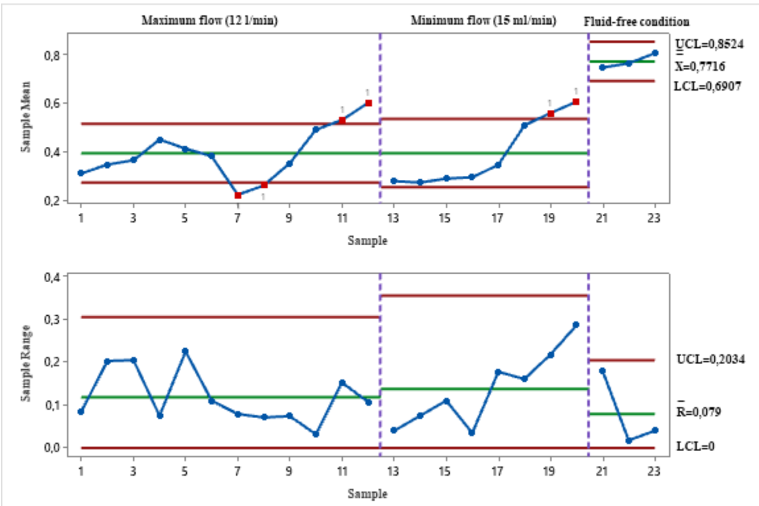
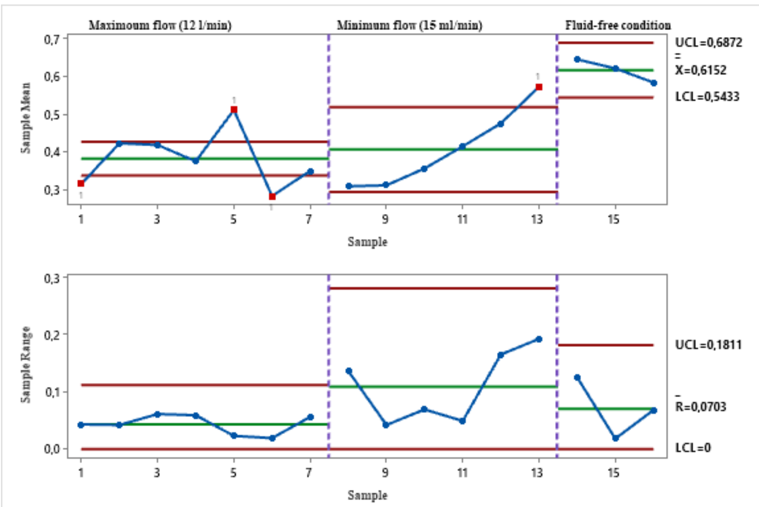



Figure 5. Values of $R_a(\mu m)$ obtained in the experiment with $V_c = 70$ m/min



The Capability Analysis was performed for experiments with cutting speeds of 60, 65 and 70 m/min using maximum flow rate, according to Figures 6,7 and 8, to verify in which condition the process operates within the defined specifications, according to Montgomery (2016), in the study of the capacity it is relevant to differentiate a stable process from capable process.

It can be observed that the process with speeds rate equal to 60 and 65 m/min, despite being considered stable and it is partially incapable to operate within the specification limits, with indexes $C_{pk}$ and $C_P$ less than 1 (one). In this way it is not able to produce with the surface quality specified by the project.

Figure 6. Process Capability Analysis for $V_c$ = 60 m/min

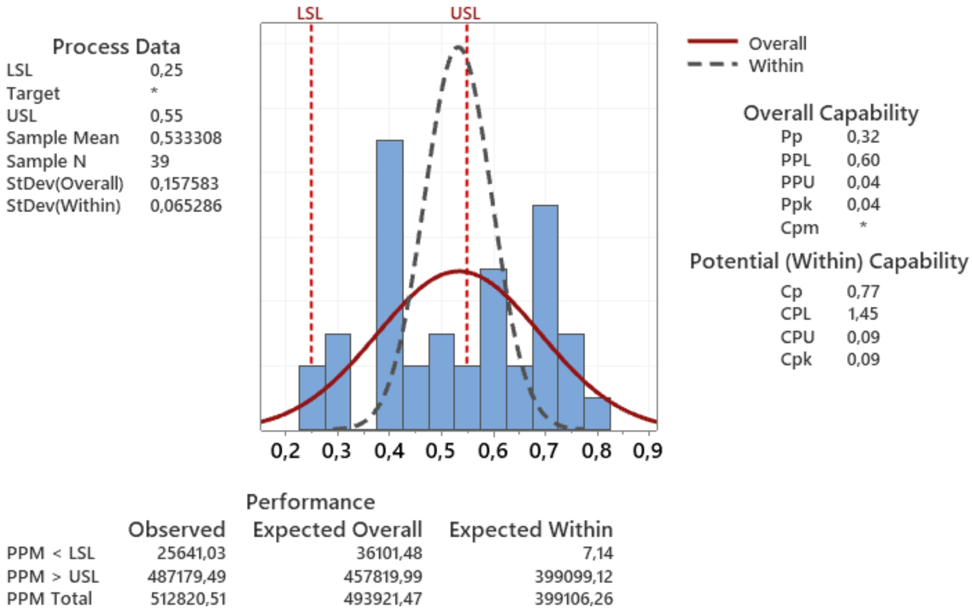



Figure 7. Process Capability Analysis for $V_c = 65$ m/min

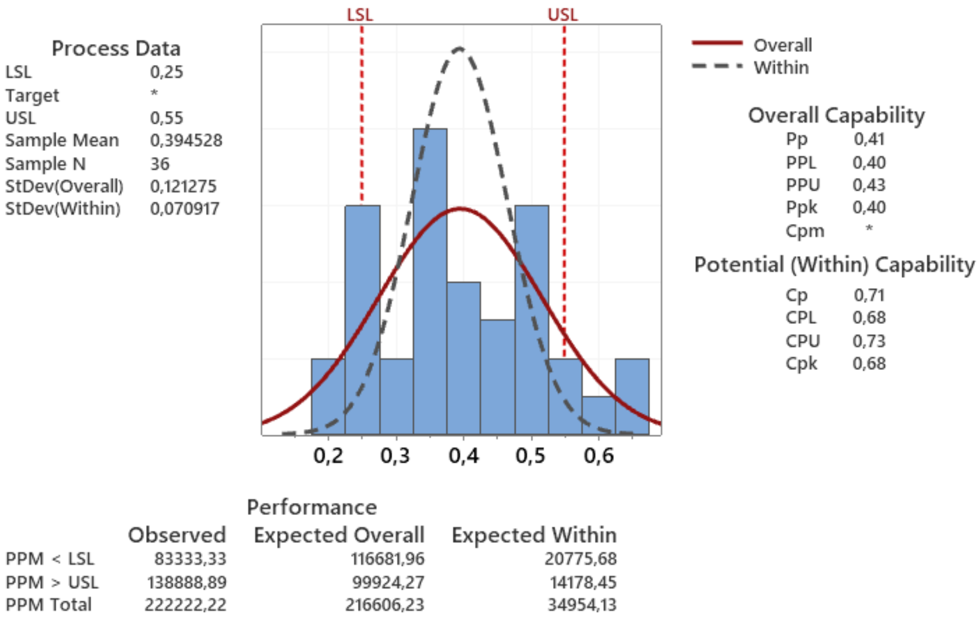
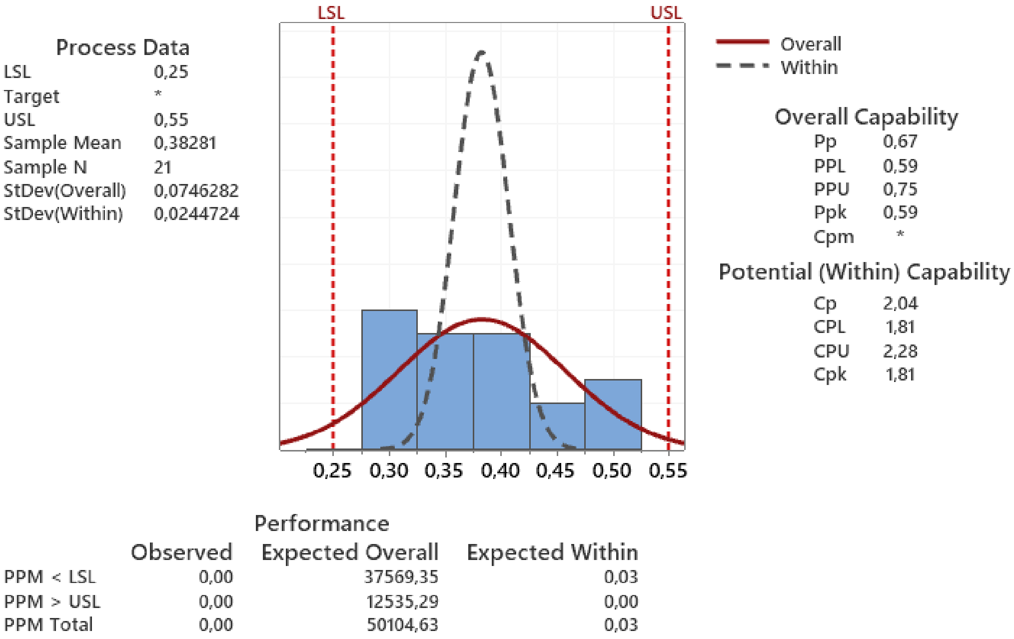


Figure 8. Process Capability Analysis for $V_c$ = 70 m/min




It was possible to obtain the capability analysis through the application of the Control Charts, a moderate stability was verified in the processes with cutting speeds of 65 m/min and 70 m/min for the minimum flow rate. In addition, it was also obtained the analysis of the capacity of the processes considered stable to operate within the required specification of roughness of the part between 0.25 and 0.55 µm, showing that only the process with a speed of 70 m/min is able to operate within the specified limits and meets the quality required by the project.

Statistical analyses revealed that, despite obtaining $R_a$ values outside the control limit, the project can be considered, because in the experiment roughness values were perceived below that specified in the project. This fact becomes a gain due to roughness requiring the lowest possible values in terms of surface quality, demonstrating that, even though the process is difficult to be controlled, it is possible to manufacture the parts according to specified the project.

## CONCLUSION

The experiments with cutting speeds $V_c$ = 65 m/min and $V_c$ = 70 m/min were considered capable of meeting the specifications. It is noticed that even stable processes may not be able to meet the defined specifications. Considering the quality of the surface measured for $R_a$ roughness, values below the specified limits can be considered in the design. Regarding the end milling process, it can be affirmed that the use of cutting fluid helps in reducing roughness values. The lowest observed $R_a$ values were obtained with the minimum flow rate and maximum flow during the experiment.

The application of minimum cutting fluid flow, in addition to obtaining good stability in the process, contributing to the costs of the operation and the health of the operators. The feed per tooth ($f_z$) = 0.10 mm/tooth and the cutting speeds ($v_c$) at 70 m/min minimizes the seasonality condition in the roughness of the surface, being as specified by the design. The cutting fluid in end milling help dissipate the heat generated, having the cooling and lubricating capacity of the machine tool, contribuing positively to increase the useful life obtaining the highest number of passes.

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## RESPONSIBILITY NOTICE

The authors are solely responsible for the information included in this work.

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**Bárbara Salvador Barros da Silva**[1]
d2019010014@unifei.edu.br
**Gustavo Rocha Queiroz**[1]
gustavoqueiroz@unifei.edu.br
**Harue Genghini Shibuta**[1]
harueshibuta@unifei.edu.br
**Leonardo Albergaria Oliveira**[1]
leoalber@unifei.edu.br
**Tarcísio Gonçalves de Brito**[1]
tgbrito@unifei.edu.br
**Thaisy Emanuele Benicio**[1]
thaisyebenicio@unifei.edu.br

[1]IEI-UNIFEI-Universidade Federal de Itajubá. Campus Avançado de Itabira. Rua Irmã Ivone Drummond, nº 200. CEP:35903-087. Itabira-MG[1]

***Abstract.***

*Milling is one of the most used processes in metal machining because it allows high productivity and low cost. In this scenario, duplex stainless steels UNS S33205 have been gaining prominence for being cost-effective, although their low machinability influences the final product. In order to guarantee the surface quality of the machined parts, it is necessary to have planning and control of the cutting parameters in order to obtain the lowest values of roughness during the process. For this, Statistical Control becomes indispensable for monitoring the variables of the project. Aligned in these conditions, this paper aims to carry out a statistical analysis of the Ra surface roughness to evaluate the quality of the machined surface in the end milling process of duplex stainless steel UNS S32205. Such analysis is performed using Control Charts and indices for Capability Analysis, seeking the best condition of the cutting speed and the amount of fluid as an input parameter. It was possible to verify moderate stability in the processes with speeds rate of 60 m/min, 65 m/min and 70 m/min both for the minimum flow. Despite obtaining points outside the lower control limit, these meant a gain in quality for the project. Only the process with a speed of 70 m/min was able to operate within the specified surface roughness limits of the part between 0.25 and 0.55 µm.*

***Keywords:*** *Capability analysis, Milling. Roughness, Control charts, duplex stainless steel UNS S32205.*