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Statistical Modeling and Multi-Objective Optimization of Thermally Assisted End Milling of 254 SMO Super Austenitic Stainless Steel

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Abstract: Thermally assisted machining (TAM) promotes controlled thermal softening and can improve the machinability of difficult-to-cut materials. This study investigates the effects of axial depth of cut (a_p), feed per tooth (f_z), and heating temperature (T) on machining forces and surface roughness during end milling of 254 SMO super austenitic stainless steel. A three-factor Box–Behnken Design was applied, followed by analysis of variance, response surface modeling, and multi-objective optimization. Results showed that a_p dominated static force, whereas f_z had the greatest influence on dynamic force and its quadratic effect was the most significant for surface roughness. Heating temperature was not statistically significant as an isolated factor; however, increasing T up to 200 °C reduced forces and roughness under suitable cutting conditions. SEM and 3D topography showed more uniform feed marks and reduced adhesion, debris, and smearing under optimized conditions. Two strategies were validated experimentally: the force-oriented condition ($a_p = 0.2$ mm, $f_z = 0.04$ mm/tooth, $T = 169$ °C) predicted $\mu F_U = 83$ N and $\Delta F_U = 42$ N, while the surface-quality condition

($a_p = 0.5$ mm, $f_z = 0.08$ mm/tooth, $T = 200$ °C) predicted $R_a = 0.16$ μ m and $R_z = 1.26$ μ m. Validation errors below 5% confirmed reliability.

Keywords: 254 SMO super austenitic stainless steel, end milling, thermally assisted machining, surface integrity, process optimization, Box-Behnken Design.

1 Introduction

Super austenitic stainless steel (SASS) is a class of metallic materials known for high resistance to pitting corrosion, characterized by high levels of chromium, nickel, molybdenum, and nitrogen, with iron content below 50% [1]. Alloys such as AL-6XN, 254 SMO, 654 SMO, and 904L are widely used in sectors that require materials with high resistance to aggressive environments, including the chemical, pharmaceutical, petrochemical, naval, and aerospace industries [2, 3]. Conversely, SASS is a material with low machinability due to its high ductility, low thermal conductivity, strong tendency to work hardening, and high mechanical strength [4, 5]. These characteristics lead to challenges, such as increased specific cutting pressure, formation of long, serrated chips, occurrence of built-up edge (BUE), increased tool wear rate, and reduced workpiece surface quality [6].

The complexity of the SASS machining process requires careful definition of cutting parameters, because small variations in feed rates, depths of cut, and temperatures in the cutting zone can lead to significant changes in machining forces, tool life, and surface finish [7, 8]. Feed rate is widely recognized as one of the most significant cutting parameters, since increasing it raises the uncut chip thickness, expands the tool-workpiece contact area, increases the material removal rate, and intensifies machining forces, while often degrading surface quality. Depth of cut also directly influences machining forces and the material removal rate, potentially accelerating tool failure mechanisms when combined with high mechanical loads. Finally, increasing the cutting speed alters the thermal regime of the process; while this can reduce forces due to thermal softening of the material, it may also intensify tool wear mechanisms caused by high temperatures at the tool-chip interface, particularly in dry machining [9, 10]. In this context, assessing machining forces is essential because it provides information on process stability, power consumption, and tool loads, in addition to serving as an important indicator of tool wear [11]. Tool life assessment

is also relevant because the low thermal conductivity of the SASS, high heat generation during cutting, and chemical affinity between tool-workpiece materials lead to wear mechanisms, BUE formation, and thermal fatigue, thereby compromising productivity and increasing machining costs [10]. Surface finish, in turn, is a critical parameter for components used in harsh environments, as it directly influences fatigue, wear, and corrosion resistance [1]. Another pertinent aspect is the high work-hardening trend of SASS. Intense plastic deformation during machining hardens the surface layer. This increases cutting resistance in subsequent runs, raises machining forces, accelerates tool wear, and hinders chip breaking. Consequently, the machinability and surface quality of the workpiece are negatively affected [6, 12].

The introduction of thermally assisted machining (TAM), which aims to soften the cutting zone through controlled heating, has been a promising alternative for mitigating the adverse effects of work hardening and improving the machinability of these materials [13, 14]. Localized heating of the cutting zone reduces the material's shear strength, machining forces, tool wear rate, and tendency toward BUE formation, while promoting chip breaking and improving workpiece surface quality [15, 16]. However, the thermal and mechanical behavior of SASS during TAM depends strongly on the relationship between the material's heating and plastic deformation temperatures, as well as on complex interactions with the aforementioned cutting parameters [17-19].

Passari et al. [19] investigated 254 SMO thermo-assisted end milling by evaluating machining forces, tool wear, and surface quality under controlled workpiece heating at 200 °C. The authors observed that TAM reduced machining forces by an average of 18.4% compared with dry cutting, performed similarly to nanofluid minimal quantity lubrication (NMQL), and increased tool life relative to dry cutting. However, the technique produced higher roughness values, associated with the formation of adhered material (chip debris) and defects such as smearing and side flow. Despite the promising results, the main limitation of the study was the fixed temperature (200 °C), which did not explore the influence of different heating levels on material behavior and process quality. Balasubramaniyan and Rajkumar [2] analyzed laser-assisted end milling of 904L by examining machining forces, tool wear, and surface integrity. The results showed that localized heating significantly reduced forces and slowed the wear rate, suggesting that the increased ductility induced by material heating favors plastic chip deformation. However, elevated temperatures, when not properly controlled, can cause material adhesion and degrade surface quality. Furthermore, the study was limited to a specific power configuration and laser parameters and did

not explore different thermal and cutting conditions, limiting a more comprehensive understanding of these interactions in SASS machining.

Given the complexity of SASS machining processes, applying statistical techniques to systematically evaluate interactions among thermal and cutting conditions that identify optimal machining parameters is beneficial. Among these techniques, Response Surface Methodology (RSM) enables mathematical modeling and analysis of the simultaneous effects of multiple factors on one or more response variables, allowing for the quantification of individual effects, interactions, and quadratic effects, as well as the prediction of process behavior within the experimental region under investigation [20]. Box-Behnken Design (BBD) is highlighted in this context because it enables, with fewer runs, the analysis of linear and quadratic effects and interactions among controllable factors such as heating temperature, feed per tooth, and depth of cut, while simultaneously reducing machining forces and surface roughness [21, 22]. Furthermore, multivariate optimization enables the determination of machining conditions that reconcile frequently conflicting responses (e.g., minimizing surface roughness and maximizing material removal rate), thereby avoiding single-variable optimization and promoting a more robust and representative selection of processing conditions for industrial applications [20]. Therefore, although TAM has already been explored in difficult-to-cut materials, studies investigating the integrated influence of these factors on SASS remain scarce, and analyses often have limited statistical scope, providing an incomplete view of the process [23, 24].

The bibliometric analysis in the **Online Resource 1** reinforces this research gap. The literature review indicates that studies on SASS primarily focus on corrosion, microstructure, phase precipitation, and metallurgical properties. However, studies on machining SASS constitute a significantly smaller share of the scientific output. Complementarily, the mapping of TAM shows a significant increase in publications in recent years (although largely concentrated on titanium alloys and nickel-based superalloys), with reduced representation of SASS. Furthermore, the analysis of keyword co-occurrence networks reveals no established link between terms related to SASS and TAM, suggesting that thermally assisted machining of super austenitic stainless steels has not been thoroughly explored.

Thus, the present study aims to investigate the combined effects of heating temperature, feed per tooth, and axial depth of cut on end milling of 254 SMO using the Box-Behnken Design (BBD) for experimental planning and statistical analysis. The responses considered were machining

forces (static and dynamic) and 2D surface roughness (R_a and R_z parameters) which were analyzed to identify the optimal machining parameters for efficient machining of this SASS. Scanning electron microscopy texture images and focus variation microscopy surface topographies were also obtained to complement the analysis of the machined surface quality. This investigation intends to contribute to a better understanding of interactions among process variables and to the development of more effective and economical machining strategies for SASS.

2 Materials and methods

Outokumpu Ultra® 254 SMO workpieces with dimensions of 70 x 30 x 10 mm were used. **Tab. 1** presents the chemical composition of the material, as reported in the manufacturer's inspection certificate. Additional properties include a hardness of 160 HB, a pitting resistance equivalent number (PREN) of 43, a density of 8.0 g/cm³, a modulus of elasticity of 195 GPa, and a thermal conductivity of 14 W/(m·°C).

Tab. 1 Chemical composition of 254 SMO super austenitic stainless steel.

Values	C	Mn	P	S	Si	Cr	Ni	Mo	N	Cu
Max.	0.020	1.00	0.03	0.010	0.80	20.50	18.50	6.50	0.22	1.00
Std.	0.012	0.48	0.02	0.001	0.38	20.12	17.76	6.02	0.20	0.69
Min.	-	-	-	-	-	19.50	17.50	6.00	0.18	0.50

End-milling of SASS was performed on a ROMI Discovery 308 machining center with a maximum power of 5.5 kW and a maximum spindle speed of 4000 rpm. A Walter Tools Xtra-tec® end-mill tool with a 20 mm nominal diameter was employed, fastening two Walter Tools Tiger-tec Silver® PVD-TiAlN/Al₂O₃-coated carbide inserts (grade SM35) with a 0.8 mm tool-nose radius (r_ϵ), a 0.04 mm cutting-edge radius (r_β), and a 1.2 mm wiper facet. Tool life was not treated as a response variable because RSM requires eliminating variability factors that could mask the effects of the factors under investigation. Thus, the insert edges were replaced according to a schedule before significant tool wear occurred, ensuring that any observed differences could be attributed solely to the heating conditions and the cutting parameters under evaluation.

The experimental procedure employed a Box-Behnken Design (BBD) based on three controllable factors (a_p , f_z , and T), each at three levels (**Tab. 2**). The selected machining parameter

ranges followed tool and material manufacturer recommendations, as well as references from previous studies on SASS machining. A preliminary study indicated that v_c had a weak influence on the investigated response variables (force and roughness) compared with the effects of a_p , f_z , and T . Consequently, the middle level of the previously studied range (60 to 140 m/min) was selected (100 m/min) to reduce experimental variability and isolate the effects of the factors chosen for the statistical design [8]. Temperature selection followed established literature concepts for determining extreme parameters: $T = 20\text{ }^{\circ}\text{C}$ was considered the ambient temperature, while $T = 200\text{ }^{\circ}\text{C}$ represented the temperature used in thermally assisted machining (TAM). The upper limit (also used in a previous study) was defined as approximately half the temperature at which significant microstructural changes begin to occur in SASS [19]. This allowed evaluation of heating benefits on machinability without compromising the material's metallurgical integrity [1].

Tab. 2 Natural and coded levels of the BBD input factors.

Controllable Factors	Notation	Unit	Levels		
			Low (-1)	Middle (0)	High (+1)
Axial depth of cut	a_p	mm	0.2	0.6	1.0
Feed per tooth	f_z	mm/tooth	0.02	0.06	0.10
Temperature	T	$^{\circ}\text{C}$	20	110	200

Statistical analyses were performed using Minitab[®] 22 software, employing BBD to randomize 15 experimental runs involving the controllable input factors (**Tab. 3**). Three runs were conducted with all three factors at the middle level (center point) to assess the study's repeatability (runs 3*, 10*, and 13*). In each run, the three controllable factors were set to three predefined levels, ensuring that no input parameters would be at low or high levels simultaneously. Analysis of Variance (ANOVA) was used to determine the influence of each input variable and their interactions on the responses obtained during end milling of 254 SMO.

For temperature management, the workpiece was heated in a controlled manner to the target temperature (110 $^{\circ}\text{C}$ or 200 $^{\circ}\text{C}$), ensuring that the average temperature field varied by no more than approximately 5%, even with changes in the axial depth of cut. Thus, a workpiece fixture was clamped directly onto the piezoelectric dynamometer. This fixing device contains an electric-resistance workpiece heating system (up to 3.0 kW, controlled by a potentiometer) and an internal cooling system (allowing the dynamometer to be refrigerated without compromising the

equipment's stability). The surface temperature was monitored continuously using an Electrophysics EZTherm thermographic device with a sensitivity of 0.08°C , a measurement range of -20 to 500°C , and an image refresh rate of 30 Hz . The emissivity value ($\epsilon = 0.25$) was determined experimentally using the surface temperature measured with a K-type thermocouple with a measurement range of -200 to 1260°C . This ensured validation of the recorded values and confirmed the steady-state condition once the workpiece reached thermal stability [19]. The experimental setup is illustrated in **Fig. 1**.

Tab. 3 Experimental parameters.

Run	a_p (mm)	f_z (mm/tooth)	T ($^{\circ}\text{C}$)
1	0.2	0.06	20
2	1.0	0.06	20
3*	0.6	0.06	110
4	0.6	0.02	20
5	0.6	0.10	20
6	0.2	0.02	110
7	1.0	0.02	110
8	0.2	0.10	110

Run	a_p (mm)	f_z (mm/tooth)	T ($^{\circ}\text{C}$)
9	1.0	0.10	110
10*	0.6	0.06	110
11	1.0	0.06	200
12	0.2	0.06	200
13*	0.6	0.06	110
14	0.6	0.10	200
15	0.6	0.02	200

*Controllable factors at the central point (0,0,0)

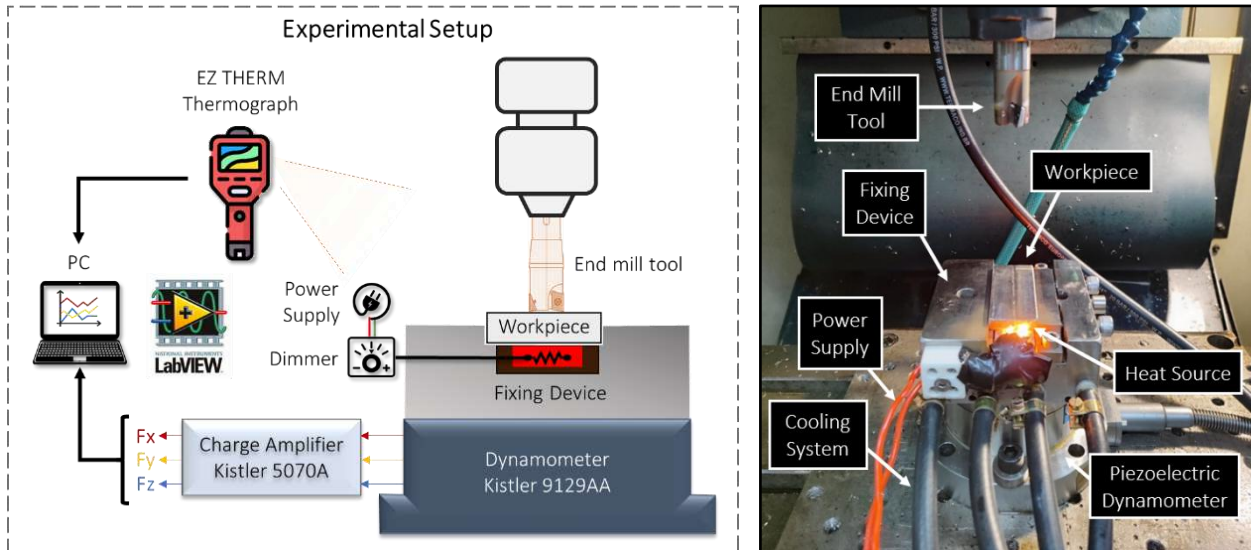


Fig. 1 Experimental setup

Orthogonal components of the machining force signal (F_x, F_y, F_z) were acquired using a Kistler

9272 piezoelectric dynamometer. These analog signals were conditioned with a Kistler 5070A charge amplifier and collected via a Measurement Computing PCIM-DAS 1602/16 data acquisition board installed in a dedicated microcomputer. Finally, the data were processed using LabVIEW 9.0 software. A sampling rate of 1.0 kHz was used. The resultant force (F_R) was calculated using **Eq. (1)**, and the machining force was determined by **Eq. (2)**. To obtain the static machining force (μF_U), the arithmetic mean of 2,000 data samples of F_R collected during the stable machining interval (i.e., excluding tool entry and exit) was calculated. Fluctuations in machining force were investigated based on the dynamic machining force (ΔF_U), defined as $\Delta F_U = 1.96 \cdot \sigma$ (95% confidence interval), where σ is the standard deviation of the F_R force over the same interval.

$$F_R = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (1)$$

$$F_U = \mu F_U \pm \Delta F_U \quad (2)$$

Two-dimensional surface roughness parameters (R_a and R_z) were measured after milling using a Mitutoyo SJ-201 stylus profilometer at a resolution of 0.01 μm . A 0.8 mm sampling length and a 4 mm evaluation length were set in accordance with DIN EN ISO 4288 ($0.1 < R_a \leq 2.0 \mu\text{m}$ and $0.5 < R_z \leq 10 \mu\text{m}$). Five measurements were taken on the machined surface for each run, with the stylus traversing the surface perpendicular to the tool feed direction to cross the feed marks and ensure representative roughness measurements.

To validate the multi-objective optimization models, the optimal cutting conditions were determined using the desirability function within the experimental domain defined by the BBD. Two independent optimization strategies were used to minimize machining forces (μF_U and ΔF_U) and 2D surface roughness (R_a and R_z). For each optimized condition, three additional validation runs were conducted using the predicted cutting parameters, and the experimental results were reported as mean $\pm$ standard deviation. The predicted values were then compared with the data measurements to assess the predictive capability and reliability of the proposed RSM models.

To complement the analysis of machined surface quality, SEM images of the machined surfaces were acquired using a Carl Zeiss EVO[®] MA10 scanning electron microscope at 150x magnification. Representative samples were selected to support the discussion of end milling under different cutting conditions. Samples 7 and 12 were chosen to represent the worst and best surface finishes obtained after 15 runs (**Tab. 3**), respectively. Additional images were acquired from the

validation samples under the force and roughness optimized conditions. Furthermore, samples 2 and 11, which differ only in heating temperature, were analyzed to assess the influence of thermal assistance on surface generation. Additionally, three-dimensional textures of the machined surfaces were acquired using focus variation interferometry with Bruker Alicona InfiniteFocus® G5. This optical technique reconstructs the surface by varying the focal plane during scanning, enabling 3D reconstruction and the determination of surface texture parameters (the equipment combines form and roughness measurements into a single system with high vertical and lateral resolution) in accordance with the ISO 25178 standard. Key 3D surface roughness parameters are the arithmetical mean height (S_a), the root-mean-square height (S_q), and the maximum peak-to-valley height (S_z) [25]. The samples analyzed were the same as those examined via SEM imaging.

3 Results and discussion

3.1 Response Variables

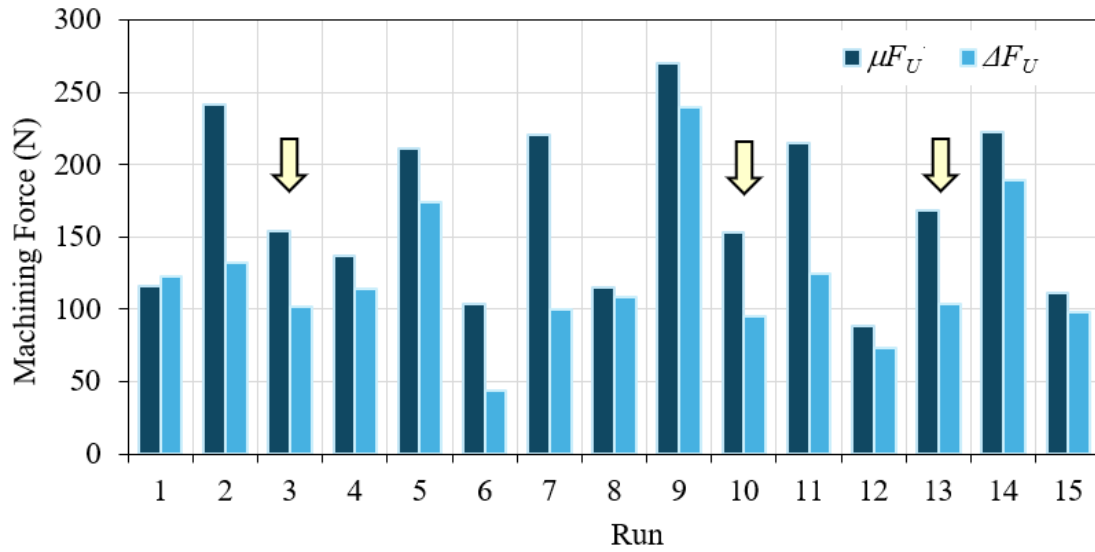
Tab. 4 presents the force and roughness data measured during the experiment. The lowest machining force and surface roughness were recorded in run 12 (low a_p , middle f_z , and high T). Conversely, run 6 (low a_p , low f_z , middle T) produced the second-lowest machining force but the second-highest surface roughness. This indicates that lower axial depth of cut (a_p) and heating temperature (T) benefit both, whereas lower feed per tooth (f_z) reduces force but increases roughness. These results will be properly discussed in the following subsections.

3.1.1 Machining forces

Fig. 2 shows the static (μF_U) and dynamic (ΔF_U) force values reported in **Tab. 4**. The lowest μF_U and ΔF_U values were recorded in run 12 (89 N and 73 N), with low a_p (0.2 mm), middle f_z (0.06 mm/tooth) and high T (200 °C), while the highest values were observed in run 9 (270 N and 240 N), with high a_p (1.0 mm), high f_z (0.10 mm/tooth) and middle T (110 °C). Considering the runs at the central point (machining with all controllable input variables at the middle level), the mean values were $\mu F_U = 158.3$ N and $\Delta F_U = 100.3$ N, with maximum variations between runs (3*, 10*, 13*) of 9.3% and 8.3%, respectively.

Tab. 4 Response variables as a function of input parameters

Run	a_p (mm)	f_z (mm/tooth)	T (°C)	μF_U (N)	ΔF_U (N)	R_a (μm)	R_z (μm)
1	0.2	0.06	20	116	123	0.49 ± 0.14	2.59 ± 0.43
2	1.0	0.06	20	242	132	0.36 ± 0.02	2.11 ± 0.22
3*	0.6	0.06	110	154	102	0.34 ± 0.08	2.26 ± 0.55
4	0.6	0.02	20	137	114	0.27 ± 0.02	1.51 ± 0.12
5	0.6	0.10	20	211	174	0.41 ± 0.03	2.33 ± 0.33
6	0.2	0.02	110	104	44	0.90 ± 0.14	5.69 ± 0.32
7	1.0	0.02	110	221	100	1.07 ± 0.19	8.49 ± 1.18
8	0.2	0.10	110	115	109	0.58 ± 0.25	3.00 ± 0.92
9	1.0	0.10	110	270	240	0.70 ± 0.01	3.74 ± 0.48
10*	0.6	0.06	110	153	95	0.19 ± 0.03	1.43 ± 0.26
11	1.0	0.06	200	215	125	0.24 ± 0.02	1.57 ± 0.04
12	0.2	0.06	200	89	73	0.16 ± 0.01	1.31 ± 0.08
13*	0.6	0.06	110	168	104	0.24 ± 0.04	1.64 ± 0.31
14	0.6	0.10	200	223	189	0.33 ± 0.02	2.38 ± 0.34
15	0.6	0.02	200	111	98	0.69 ± 0.09	4.30 ± 0.63



Run	1	2	3*	4	5	6	7	8	9	10*	11	12	13*	14	15
a_p (mm)	0.2	1.0	0.6	0.6	0.6	0.2	1.0	0.2	1.0	0.6	1.0	0.2	0.6	0.6	0.6
f_z (mm/z)	0.06	0.06	0.06	0.02	0.10	0.02	0.02	0.10	0.10	0.06	0.06	0.06	0.06	0.10	0.02
T (°C)	20	20	110	20	20	110	110	110	110	110	200	200	110	200	200

Fig. 2 μF_U and ΔF_U values of thermally assisted end milling

Comparatively, it is observed that the μF_U and ΔF_U values exceeded 210 N and 120 N in runs 2, 5, 9, 11, and 14. These results are due to the larger cross-sectional area ($\geq 0.060 \text{ mm}^2$) in all these combinations. In the highest static and dynamic forces (run 9), the area was 0.100 mm^2 (high a_p and high f_z). However, in run 7, the area is 0.020 mm^2 ; thus, the plowing effect associated with low f_z and high a_p probably caused the increase in static force (221 N). In this case, a very small f_z suggests that the uncut chip thickness (h) is not sufficiently greater than the cutting-edge radius (r_β) to shear the chip without deforming it in the cutting wedge. This effect can increase the specific cutting pressure, reduce tool life, and damage the surface finish, as previously reported for difficult-to-cut stainless steels by Passari et al. [19] and Yun et al. [26].

Despite run 8 results in the same area (0.020 mm^2), there is no plowing effect due to high f_z and low a_p , resulting in a minor μF_U (115 N). In run 1 (low a_p and middle f_z), the cross-sectional area was 0.012 mm^2 , generating a static force of 116 N and a dynamic force of 123 N; this was the only run in which the response variable $\Delta F_U > \mu F_U$, probably due to the rapid tool-edge wear in the initial stage of machining.

Regarding the heating temperature (T), although it has no significant influence on the forces, comparing runs at different temperatures (20°C and 200°C) allows us to analyze these effects. For runs 1 and 12 (low a_p and middle f_z), the increase in temperature resulted in a decrease of 23.3% and 40.7% in the μF_U and ΔF_U values, respectively. Similarly, the increase in T from run 2 to 11 (high a_p and middle f_z) caused decreases of 11.2% and 5.3%, while from run 4 to 15 (middle a_p and low f_z), the reductions were 19% and 14%. However, for runs 6 and 14 (middle a_p and high f_z), the increase in temperature resulted in an increase of 5.7% and 8.6% in the μF_U and ΔF_U values. It is observed that temperature has a greater influence when the cross-sectional area is smaller (0.012 mm^2). When this area is larger (0.060 mm^2), with increasing temperature, high a_p had a specific effect on μF_U (runs 2 and 11), and high f_z had some influence on ΔF_U (runs 5 and 14).

3.1.2 Two-dimensional surface roughness

Fig. 3 shows the average roughness (R_a) and mean peak-to-valley height (R_z) values listed in **Tab. 4**. A consistent relationship is observed between these two amplitude parameters, where R_z (in gray) remains approximately 6.4 times greater than R_a (in green). This ratio indicates that, despite variations in cutting conditions, the machined surface exhibits relatively homogeneous behavior in the peaks-and-valleys distribution, maintaining a predictable correlation between these roughness parameters [11].

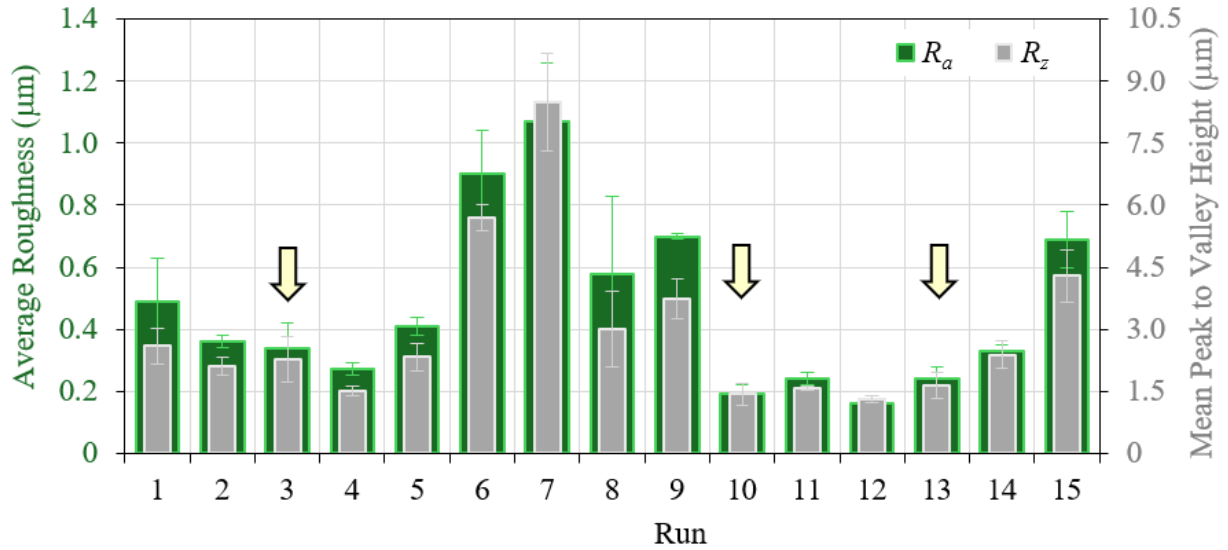


Fig. 3 R_a and R_z values of thermally assisted end milling.

The lower roughness values ($R_a < 0.30 \mu\text{m}$ and $R_z < 1.92 \mu\text{m}$) were measured after runs with middle f_z and high T , i.e., sample 12 (low a_p) and sample 11 (high a_p), in addition to sample 4 (middle a_p , low f_z and low T) and the mean R_a and R_z values measured on samples at the central point. In sample 12, the lowest overall values were recorded ($R_a = 0.16 \pm 0.01 \mu\text{m}$ and $R_z = 1.31 \pm 0.08 \mu\text{m}$), indicating that the combination of low a_p , middle f_z , and high T provided the best surface finish among the 15 combinations evaluated. Similar results were obtained in sample 11 ($R_a = 0.24 \pm 0.02 \mu\text{m}$ and $R_z = 1.57 \pm 0.04 \mu\text{m}$) and in the mean values measured among the samples 3*, 10*, and 13* ($R_a = 0.26 \pm 0.05 \mu\text{m}$ and $R_z = 1.78 \pm 0.39 \mu\text{m}$). These results suggest that the middle f_z (0.06 mm/tooth) promotes a balance between uncut chip thickness and cutting stability, resulting in low surface roughness. However, the values registered on sample 4 ($R_a = 0.27 \pm 0.02 \mu\text{m}$ and $R_z = 1.51 \pm 0.12 \mu\text{m}$) showed the opposite trend, probably due to the embrittlement of the work-hardened chip at room temperature (20 °C), which did not generate the plowing effect and favored cutting in machining with middle a_p and low f_z , in addition to not having chip debris, smearing and side flow.

Although it contributed to lower force values, low f_z (0.02 mm/tooth) did not yield the lowest

roughness, possibly due to the plowing effect [26]. Therefore, sample 7 presented the highest roughness values ($R_a = 1.07 \pm 0.19 \mu\text{m}$ and $R_z = 8.49 \pm 1.18 \mu\text{m}$), while sample 6 showed the second highest values ($R_a = 0.90 \pm 0.14 \mu\text{m}$ and $R_z = 5.69 \pm 0.32 \mu\text{m}$). At the other extremity, for high f_z (0.10 mm/tooth), intermediate roughness values were registered. For example, in sample 9, $R_a = 0.70 \pm 0.01 \mu\text{m}$ and $R_z = 3.74 \pm 0.48 \mu\text{m}$, while in sample 14, $R_a = 0.33 \pm 0.02 \mu\text{m}$ and $R_z = 2.38 \pm 0.34 \mu\text{m}$.

Comparative analysis between cutting conditions, varying only the heating temperature (T), shows that increasing the temperature (from 20 °C to 200 °C) tends to reduce the roughness values.

When assessing the surface roughness of samples 1 and 12 (low a_p and middle f_z), there was a 67.3% reduction in R_a and a 49.4% reduction in R_z . This improvement is directly associated with the lower μF_U and ΔF_U values recorded in run 12, which characterize a more stable end milling process [22]. For samples 2 and 11 (high a_p and middle f_z), the reduction was 33.3% in R_a and 25.6% in R_z . This behavior indicates that increasing the temperature improves the cutting operation under high a_p conditions, decreasing the formation of marks and irregularities on the machined surface [17, 18].

Considering samples 5 and 14 (middle a_p and high f_z), the temperature increase resulted in a 19.5% reduction in average roughness. However, there was practically no change in the mean peak-to-valley height values ($R_{z05} = 2.33 \pm 0.33 \mu\text{m}$ and $R_{z14} = 2.38 \pm 0.34 \mu\text{m}$). This behavior suggests that thermal softening promoted more uniform chip formation and reduced the average asperity height across most of the machined surface, resulting in lower R_a values. However, clear feed marks and occasional localized surface defects (such as side flow and material adhesion) were observed at a high feed per tooth (0.10 mm/tooth). Although R_z is governed by high peaks and deep valleys rather than the overall surface profile, these isolated irregularities were sufficient to maintain nearly constant R_z values. On the other hand, an increase in temperature led to a significant increase in the surface roughness values for samples 4 and 15 (middle a_p and low f_z). The 155.6% increase in R_a and the 184.8% increase in R_z demonstrate that the plowing effect is intensified at higher temperatures (due to the material's thermal softening), resulting in a deterioration of the surface finish.

3.2 Statistical Analyses

ANOVA, contour plots, and multi-objective optimization comprised the statistical analysis, revealing that heating temperature (despite not being a significant factor) positively affects forces and roughness. These issues will be detailed in the following subsections.

3.2.1 Analysis of variance

Analysis of variance (**Tab. 5**) allowed the identification of the most relevant linear, quadratic, and interaction effects of the controllable factors (a_p, f_z, T) on the response variables ($\mu F_U, \Delta F_U, R_a, R_z$). For static force (μF_U), the linear effect of axial depth of cut (a_p) was the most statistically significant parameter (p-value < 0.001), with 74.28% of the contribution, followed by the linear effect of feed per tooth (f_z), with p-value = 0.011 and 16.17% of the contribution. For dynamic force (ΔF_U), feed per tooth (f_z) was highlighted as the most influential factor, contributing 48.82% and showing high statistical significance (p-value = 0.003), followed by the linear effect of axial depth of cut (a_p), with p-value = 0.013 and 23.77% contribution. Furthermore, the quadratic effect of feed per tooth ($f_z \times f_z$) was significant at the 90% confidence interval, with a p-value = 0.081 and a contribution of 7.33%. Therefore, it can be observed that while a_p is determinant for the mean machining force in end milling of 254 SMO, f_z acts more significantly on its force fluctuations during the cutting operation.

Tab. 5 ANOVA

Factor	μF_U		ΔF_U		R_a		R_z	
	p-value	Pr. (%)	p-value	Pr. (%)	p-value	Pr. (%)	p-value	Pr. (%)
a_p	< 0.001	74.28	0.013	23.77	0.650	0.63	0.437	2.42
f_z	0.011	16.17	0.003	48.82	0.083	12.67	0.060	19.99
T	0.328	1.22	0.413	1.35	0.908	0.04	0.631	0.89
$a_p \times a_p$	0.564	0.30	0.752	0.59	0.076	11.70	0.149	8.75
$f_z \times f_z$	0.330	1.21	0.081	7.33	0.011	43.96	0.028	34.64
$T \times T$	0.986	0.00	0.225	3.24	0.172	6.86	0.184	8.07
$a_p \times f_z$	0.418	0.81	0.169	4.36	0.882	0.07	0.492	1.86
$a_p \times T$	0.992	0.00	0.414	1.34	0.581	0.94	0.802	0.24
$f_z \times T$	0.415	0.82	0.535	0.75	0.118	9.60	0.237	6.14
R^2	94.81%		91.55%		86.46%		83.00%	

For surface roughness, the quadratic effect of feed per tooth ($f_z \times f_z$) was the most significant, with p-value = 0.011 and a 43.96% contribution to R_a and p-value = 0.028 with a contribution of 34.64% to R_z . Besides, the linear effect of f_z was significant for a 90% confidence interval, with p-value = 0.083 with a 12.67% contribution to R_a and p-value = 0.060 with a 19.99% contribution to R_z . Furthermore, the quadratic effect of axial depth of cut ($a_p \times a_p$) was also significant over R_a for a 90% confidence interval, with p-value = 0.076 and contribution of 11.70%, and over R_z for an 85.1% confidence interval (8.75% contribution). These results indicate that the effect of feed per tooth on R_a and R_z is not mainly linear, but rather quadratic, i.e., it depends on other factors. Furthermore, low f_z (affecting the h/r_β ratio and plowing effect) or high f_z (influencing force fluctuations and feed marks on the workpiece) results in surface deterioration, whereas middle f_z favors a surface finish, as observed in previous analyses.

Despite the analysis of individual results suggesting that increasing the temperature may improve the surface finish when machining with a middle f_z (0.06 mm/tooth), the ANOVA shows that the heating temperature (T) did not significantly influence the roughness parameters at a confidence interval of 95% or greater. ANOVA shows that the quadratic effect $T \times T$ is significant over R_a and R_z for a confidence interval of 81.5%, and that the combination $f_z \times T$ is significant on R_a only for an 88.2% confidence interval and on R_z only for a 76.3% confidence interval.

3.2.2 Contour plots

Fig. 4 illustrates the contour plots of the machining forces, and **Fig. 5** shows those of the surface roughness as a function of the $f_z \times a_p$, $T \times a_p$ and $T \times f_z$ combinations.

Fig. 4a exhibits contour plots of the static forces (μF_U). In the $f_z \times a_p$, the combination of high a_p and high f_z results in the highest μF_U values (above 250 N). In this region, the force amplitude is due to the simultaneous increase in uncut chip thickness (h) and the volume of material removed, confirming the ANOVA results, which pointed to a_p as the predominant factor. On the other hand, reduced levels of a_p (≤ 0.6 mm) and f_z (≤ 0.05 mm/tooth) define the most favorable region, where the μF_U remains below 150 N, indicating more stable cutting conditions and less mechanical stress on the tool. In the $T \times a_p$, the increase in a_p promotes a progressive increase in μF_U , with little influence from temperature. Although the effect of temperature alone is not significant, for low a_p (≈ 0.2 mm) a region between 110 °C and 200 °C is observed where the force is below 100 N, characterizing an optimized region. Finally, in the $T \times f_z$ combination, a quadratic interaction is

observed in the region of $T \geq 65^\circ\text{C}$ and $f_z \leq 0.06$ mm/tooth, indicating greater interaction complexity. This region also indicates that with low f_z , an increase in temperature reduces μF_U .

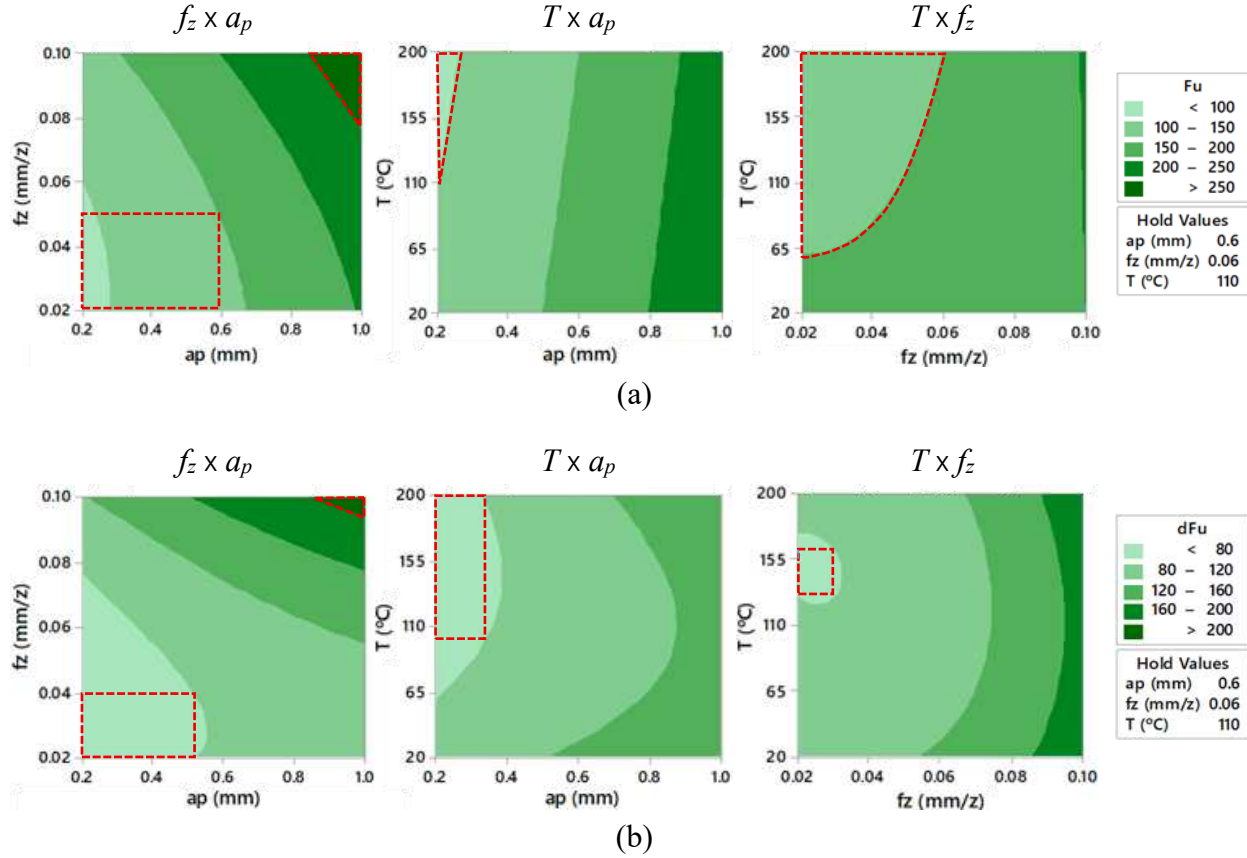


Fig. 4 Contour plots: (a) μF_U ; (b) ΔF_U

Fig. 4b shows contour plots of the dynamic forces (ΔF_U). The $f_z \times a_p$ interaction exerts a strong influence on the response, with the highest ΔF_U values observed in the region of higher a_p associated with higher f_z , where $\Delta F_U > 200$ N. This trend reinforces the combined effect of the increase in the cross-section area and the instability resulting from the removal of a larger volume of material. Considering the region with the lowest dynamic force values ($\Delta F_U < 80$ N), the rectangular region dashed in red indicates that the combination of $0.02 \leq f_z < 0.04$ mm/tooth and $0.20 \leq a_p \leq 0.52$ mm should be considered. In the $T \times a_p$ interaction, increasing a_p promotes a progressive growth in ΔF_U , where the thermal contribution is secondary compared to the predominant effect of a_p . However, again, there is an area with lower ΔF_U values delimited by $0.20 \leq a_p \leq 0.34$ mm and $101.5 \leq T < 200^\circ\text{C}$. For $T \times f_z$, the lowest ΔF_U can be achieved from the

area defined by the combination between $0.02 \leq f_z \leq 0.03$ mm/tooth and $131.5 \leq T \leq 161.5$ °C, suggesting a possible thermal softening effect of the machined material, which facilitates chip formation. However, at higher f_z , this effect is insufficient to compensate for the increased stress from the higher mechanical load, resulting in an intensification of the dynamic forces.

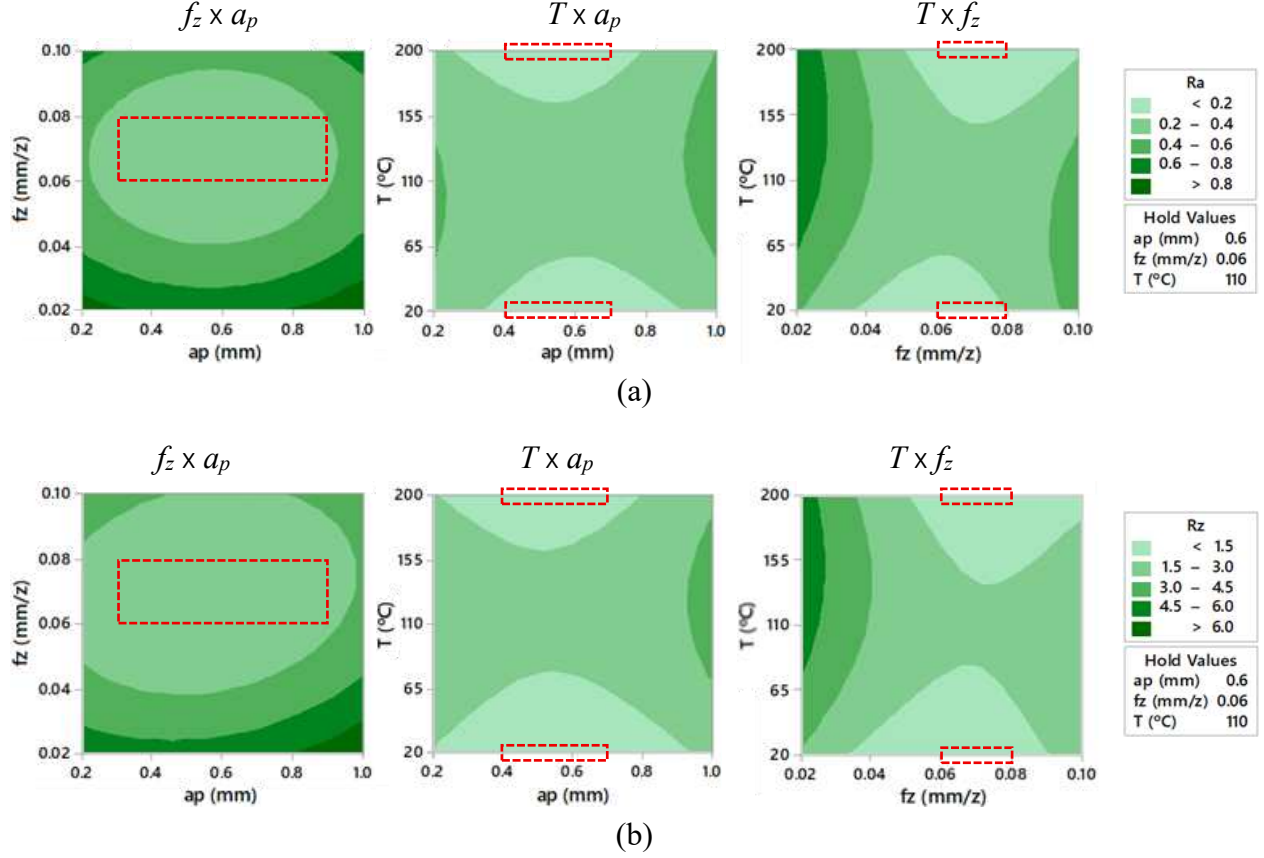


Fig. 5 Contour plots: (a) R_a ; (b) R_z

The contour plots of average roughness (R_a) and mean peak-to-valley height (R_z) as a function of the $f_z \times a_p$, $T \times a_p$, and $T \times f_z$ combinations are shown in **Fig. 5a** and **Fig. 5b**, respectively. Both amplitude parameters exhibit a very similar behavior, reinforcing a direct relationship between them, with $R_z \approx 6.5 R_a$. Regarding the same levels of cutting parameters for the two response variables, in the $f_z \times a_p$ interaction, the combination of $0.06 \leq f_z \leq 0.08$ mm/tooth with $0.3 \leq a_p \leq 0.9$ mm resulted in regions of good surface finish ($0.2 \leq R_a \leq 0.4$ μ m and $1.5 \leq R_z \leq 3.0$ μ m). On the other hand, peripheral regions of the graph, particularly those with low f_z combined with low/high a_p values, indicate the worst finishes. In the $T \times a_p$ interactions, the plots

indicate that $0.4 \leq a_p \leq 0.7$ mm, combined with high/low T , yield better finishing ($R_a < 0.2$ μm and $R_z < 1.5$ μm). A similar pattern is also observed in the $T \times f_z$ interaction, again highlighting that $0.6 \leq a_p \leq 0.8$ mm yields low roughness values, especially when combined with high/low T .

3.2.3 Multi-objective optimization

Based on ANOVA and contour plots, it was evidenced that a reduced cross-sectional area (with low f_z , low a_p , or both) and an increase in T led to lower μF_U and ΔF_U values. However, low or high f_z results in surface deterioration, whereas a middle f_z promotes better surface quality. Furthermore, increasing a_p tends to increase roughness values. Finally, an increase in temperature reduces R_a and R_z values when combined with medium f_z (regardless of a_p level). Therefore, it was decided to perform two multi-objective optimizations (A and B) to achieve optimal cutting conditions for minimum machining force (A) and minimum surface roughness (B).

Desirability is an index used in multi-objective optimization that measures how closely the obtained responses approach the ideal values previously established. This index ranges from 0 to 1, where $D = 1$ denotes the optimal condition (when all responses reach the best possible values). In contrast, values close to 0 indicate poor compliance with the optimization criteria [27]. When optimizing the input parameters to minimize static and dynamic forces, a composite desirability value of $D = 0.98$ was obtained, indicating a near-optimal condition. For individual desirability, $d = 1.0$ for μF_U and $d = 0.96$ for ΔF_U were registered, confirming that the forces were suitably optimized. The results are presented in **Tab. 6**, which shows that the predicted values fell within the variation range presented by the experimentally validated values. It is important to note that the surface roughness values measured after the validation test under the force-optimized condition were $R_a = 0.28 \pm 0.06$ μm and $R_z = 1.86 \pm 0.27$ μm , which remained within the range typically associated with finish end-milling operations.

Tab. 6 Optimization and validation of forces

a_p (mm)	f_z (mm/tooth)	T ($^{\circ}\text{C}$)	Predicted	Validated
0.2	0.04	169	$\mu F_U = 83$ N $\Delta F_U = 42$ N	$\mu F_U = 87 \pm 14$ N $\Delta F_U = 44 \pm 5$ N

By improving the controllable factors to minimize both roughness values, a composite

desirability value of $D = 0.99$ was achieved, indicating a very near-optimal condition. Assessing individual desirabilities, $d = 0.98$ for R_a and $d = 1.0$ for R_z were obtained, indicating that the roughness parameters were optimized adequately. The results are shown in **Tab. 7**, again suggesting good agreement between the optimized and validated roughness values. Analogously, the machining force values measured after the validation test under the roughness-optimized condition were $\mu F_U = 181 \pm 13$ N and $\Delta F_U = 115 \pm 2$ N. These values were substantially higher than those for the force-optimized parameters (**Tab. 6**) after the validation test, representing increases of approximately 108% for μF_U and 161% for ΔF_U .

Tab. 7 Optimization and validation of roughness parameters

a_p (mm)	f_z (mm/tooth)	T (°C)	Predicted	Validated
0.5	0.08	200	$R_a = 0.16 \mu\text{m}$ $R_z = 1.26 \mu\text{m}$	$R_a = 0.16 \pm 0.01 \mu\text{m}$ $R_z = 1.31 \pm 0.12 \mu\text{m}$

Although the roughness values under the force-optimized condition indicated an excellent surface finish ($R_a \approx 0.28 \mu\text{m}$ and $R_z \approx 1.86 \mu\text{m}$), they remained higher than those under the roughness-optimized condition after the validation test ($R_a \approx 0.16 \mu\text{m}$ and $R_z \approx 1.31 \mu\text{m}$). This result highlights the inherent trade-off between minimizing machining forces and maximizing surface quality in thermally assisted end milling of 254 SMO, making it impractical to define a single set of cutting parameters that simultaneously minimizes both responses. Consequently, adopting two independent multi-objective optimizations is justified, depending on the desired manufacturing objective, whether prioritizing lower cutting loads or superior surface quality.

The feed per tooth indicated by multi-objective optimization A ($f_z = 0.04$ mm/tooth) effectively reduced the force values by decreasing the cross-sectional area. However, it did not correspond to the f_z value that minimizes surface roughness. As demonstrated above, the best surface finish can be achieved at $f_z = 0.08$ mm/tooth, where chip formation becomes more stable and the plowing effect is minimized (uncut chip thickness greater than the cutting-edge radius).

The results of the experimental validation were quite similar to those measured for sample 12 ($R_a = 0.16 \pm 0.01 \mu\text{m}$ and $R_z = 1.31 \pm 0.08 \mu\text{m}$), which exhibited the best surface finish among the first 15 samples. The controllable factors for run 12 were $a_p = 0.2$ mm, $f_z = 0.06$ mm/tooth, and $T = 200$ °C (**Tab. 4**). This behavior reinforces the analysis of the contour plots, which showed that

a region of combination between a_p and f_z can yield lower roughness values. Notably, even with equivalent roughness values, the optimized condition is more advantageous from a production viewpoint, as it increases the material removal rate from 764 mm³/min in run 12 to 2546 mm³/min in the roughness-optimized condition, ensuring greater productivity without compromising the machined surface quality [28].

3.3 Surface Texture Analyses

Surface texture analyses were conducted using SEM and FVM. The best surface quality (sample machined under the roughness-optimized condition) showed more uniform feed marks, reduced material adhesion, less chip debris, and minimal smearing, resulting in lower 3D roughness values. These findings will be presented in detail in the following subsections.

3.3.1 SEM images

Fig. 6 compares SEM images of the end-milled surfaces of samples 7 (high a_p , low f_z , middle T) and 12 (low a_p , middle f_z , high T), which exhibited, respectively, the highest and lowest roughness values among the first 15 samples (**Tab. 4**). The sample 7 (**Fig. 6a**) shows greater irregularity, with less uniform feed marks, as well as adhered material, chip debris, and localized smearing. These features indicate that adhesion and plowing mechanisms predominate during machining. A combination of a high depth of cut and a low feed per tooth increases the contact area between the tool and the workpiece, intensifying friction and surface plastic deformation [19, 26, 29]. Similar surface alterations have been reported by Zhou [29] in milling of austenitic stainless steel, where changes in cutting parameters affected the regularity of machining marks and the occurrence of deformation and adhesion related defects. In contrast, sample 12 (**Fig. 6b**) exhibits a significantly more homogeneous surface, characterized by continuous, well-defined feed marks, minimal adhered material, and minimal smearing. The few observed defects consist of small, isolated voids, possibly resulting from localized pull-out or the removal of previously adhered material during end-mill cutting action. This morphology indicates a more stable milling process that preserves surface integrity, explaining the lower roughness values obtained under this condition. According to Sales et al. [30], stable chip formation reduces friction at the tool–chip interface, minimizes plastic deformation on the newly generated surface, and consequently improves the final surface integrity.

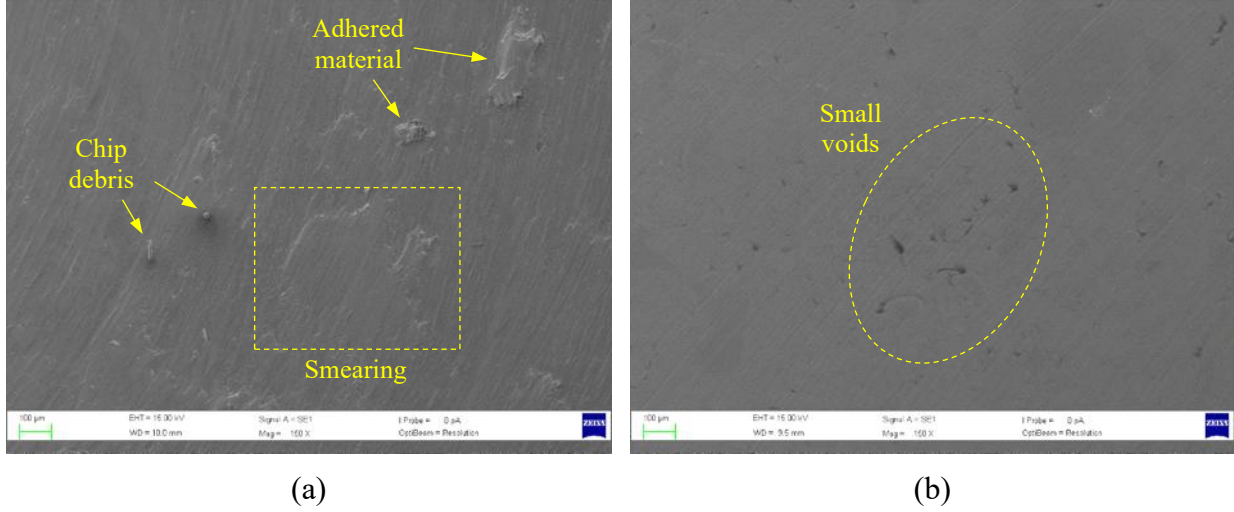


Fig. 6 SEM image of: (a) sample 7; (b) sample 12 (150x magnification)

Fig. 7 compares SEM images of the surfaces of samples 2 and 11 (**Tab. 4**), enabling separate evaluation of the temperature effect on surface integrity ($T_{02} = 20\text{ }^{\circ}\text{C}$ and $T_{11} = 200\text{ }^{\circ}\text{C}$), as the other machining parameters remained constant ($a_p = 1.0\text{ mm}$ and $f_z = 0.06\text{ mm/tooth}$). In both cases, the roughness values fall within ISO surface roughness grade N5 (R_a from 0.2 to $0.4\text{ }\mu\text{m}$). Sample 2 (**Fig. 7a**) shows continuous, uniformly distributed feed marks, with a low incidence of surface defects, minimal smearing and no adhered material. Nevertheless, sample 11 (**Fig. 7b**) shows numerous small voids distributed across the surface, along with isolated chip debris, indicating localized adhesion events followed by material pull-out. Despite these discontinuities, the tool feed marks remain regular, and no severe defects (such as cracks or intense surface plastic deformation) are observed. The presence of these voids may be linked to the rise in machining temperature, which may promote localized softening of the SASS and intensifies adhesion mechanisms at the tool-workpiece interface (as noted in previous comparisons).

Heat-assisted machining reduces the flow stress and shear resistance of the work material, facilitating plastic deformation and chip formation. However, the increased material ductility may also favor plastic flow and localized adhesion when the thermal and mechanical conditions are not properly balanced. As the cutting edge passes over the surface, some of the adhered material may be removed together with the chip, leaving small cavities or pull-out marks. Adhesion, plastic flow, and subsequent material detachment are compatible with the surface-generation mechanisms described for difficult-to-cut materials under severe thermomechanical loading [18, 19, 30].

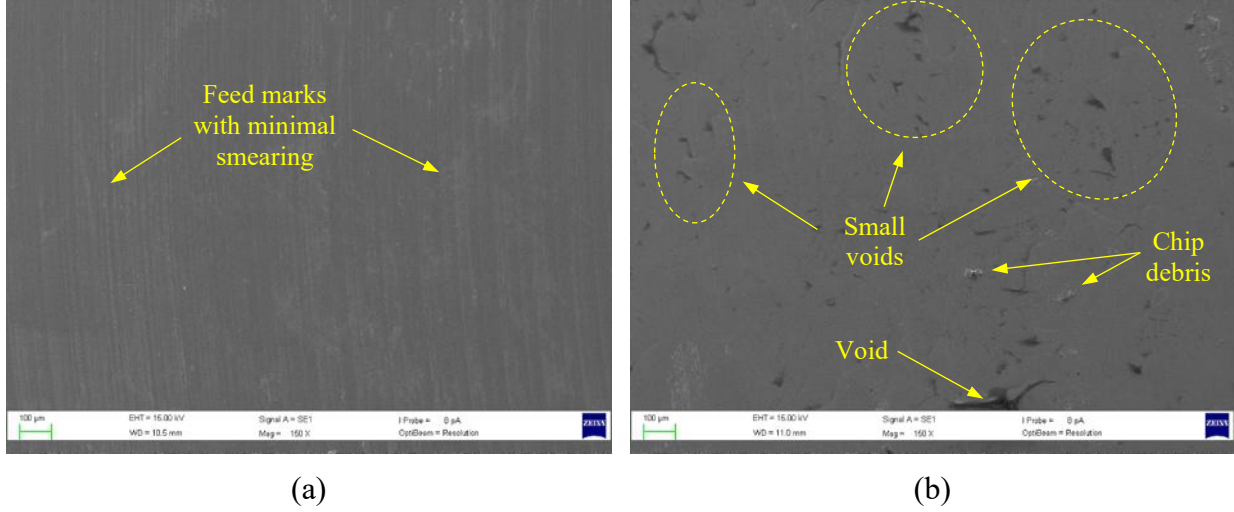


Fig. 7 SEM image of: (a) sample 2; (b) sample 11 (150x magnification)

Zhou [29] also observed that milling parameters affect the occurrence of adhesion-related surface defects and the regularity of the resulting tool marks in austenitic stainless steel. However, the reduction in shear strength achieved via thermally assisted end milling ($T_{11} = 200\text{ }^{\circ}\text{C}$) resulted in a more efficient finishing process, reflected in a 33.3% decrease in mean R_a and a 25.6% decrease in mean R_z compared to the unheated condition ($T_{02} = 20\text{ }^{\circ}\text{C}$). These results indicate that, while elevated temperatures promote micro-defects associated with material adhesion, they also reduce geometric irregularities caused by the cutting operation, leading to an overall improvement in the surface quality of the 254 SMO.

Fig. 8 compares the SEM images of machined surfaces produced under conditions derived from multi-objective optimization: force-optimized condition (**Tab. 6**) and roughness-optimized condition (**Tab. 7**). On the sample produced under the force-optimized condition (**Fig. 8a**), a relatively homogeneous surface texture is observed, with well-defined feed marks. However, small regions of adhered material, some chip debris, and a few small voids are still perceptible. These defects are low-magnitude and consistent with the measured roughness values ($R_a \approx 0.28\text{ }\mu\text{m}$ and $R_z \approx 1.86\text{ }\mu\text{m}$), indicating that the reduction in forces was achieved without significantly compromising the workpiece surface integrity. However, the condition optimized to minimize surface roughness (**Fig. 8b**) yields an even more uniform topography, with regular feed marks and practically no adhered material or smearing, resulting in the lowest roughness values in the study ($R_a \approx 0.16\text{ }\mu\text{m}$ and $R_z \approx 1.31\text{ }\mu\text{m}$). Under this optimized condition, small, isolated voids are observed on the surface, attributed to localized material pull-out or the removal of previously

adhered material. The occurrence of these cavities is similar to that observed in sample 12. This result is expected given the similarity of the conditions (specifically, $T = 200\text{ }^{\circ}\text{C}$ and middle-to-high f_z values), which enable a stable cutting regime, in addition to reducing material adhesion and plowing effect [18, 30].

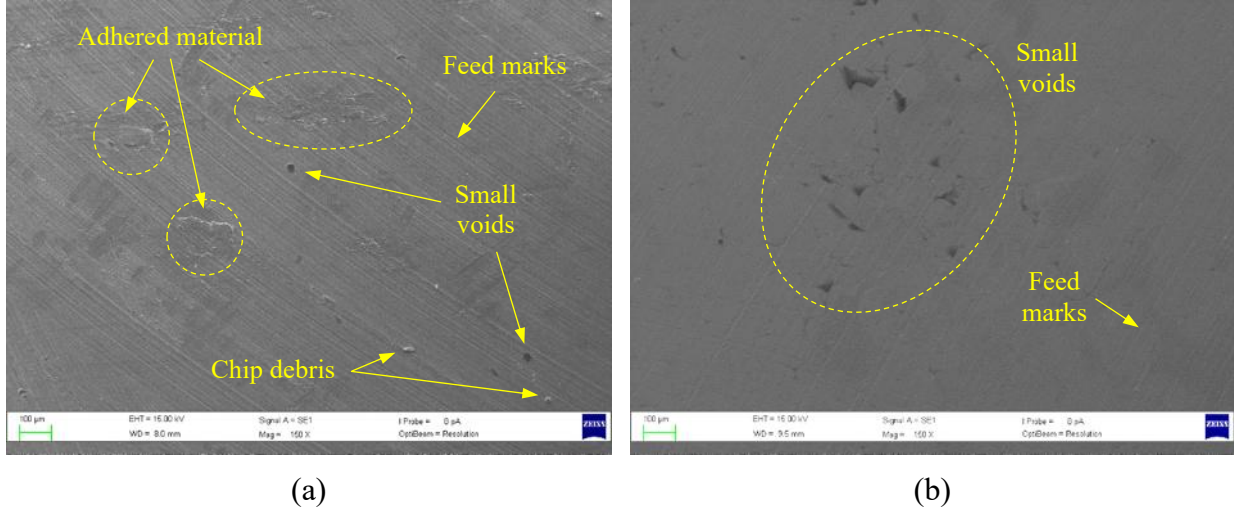


Fig. 8 SEM image of the samples under: (a) force-optimized condition; (b) roughness-optimized condition (150x magnification)

3.3.2 FVM images

Fig. 9 compares FVM images of samples 7 (highest 2D roughness) and 12 (lowest 2D roughness). Sample 7 (**Fig. 9a**) exhibits a significantly heterogeneous surface topography, characterized by prominent feed marks (correlated with the plowing effect) and by some regions with high peaks and deep valleys throughout the analyzed area. These irregularities corroborate the results obtained from SEM images (**Fig. 6a**), which revealed smearing, adhered material, and chip debris. They are consistent with higher values for the 3D roughness parameters, indicating greater dispersion in surface heights. In contrast, sample 12 (**Fig. 9b**) exhibits a much more regular and homogeneous surface texture, with continuous feed marks and less variation in surface roughness height between adjacent regions. This morphology is consistent with the SEM image analysis (**Fig. 6b**) and with the lower 2D and 3D roughness values obtained with this parameter combination (low a_p , middle f_z , high T). The regularity observed in both the SEM and FVM analyses is consistent with the effect of appropriately selected milling parameters on austenitic stainless-steel surface integrity [29]. Moreover, the improved topography can be associated with

the thermal-softening effect [18], provided that the feed remains sufficiently high to avoid predominant rubbing and plowing. Despite sample 12 exhibiting an S_z value higher than that of sample 7, this parameter is determined solely by the distance between the highest peak and the deepest valley within the analyzed area. Consequently, the presence of debris (detected by FVM as small surface peaks) directly influences the maximum peak-to-valley height [25].

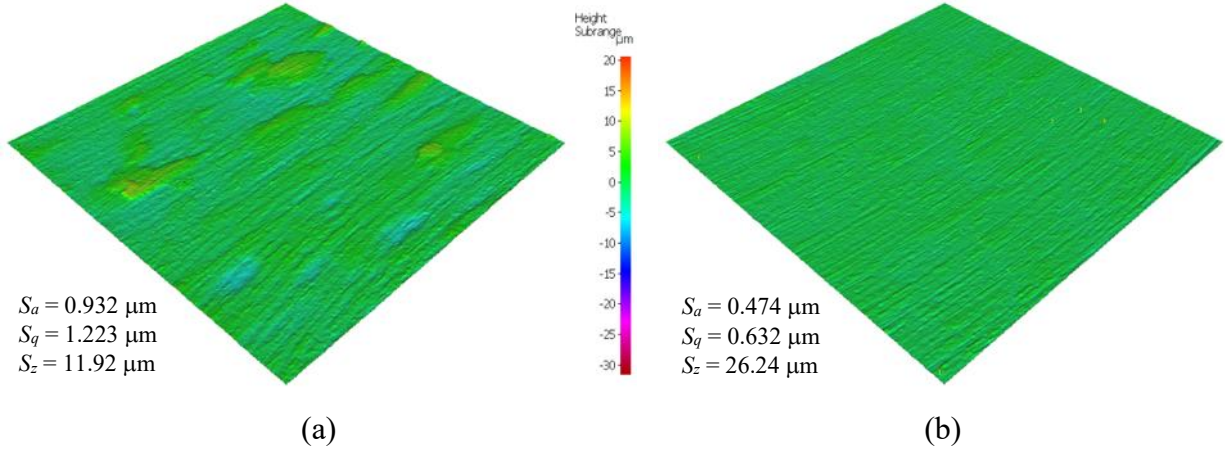


Fig. 9 FVM images of: (a) sample 7; (b) sample 12 (20x magnification)

Fig. 10 compares FVM images of samples 2 and 11, allowing an isolated assessment of the temperature effect on surface integrity ($T_{02} = 20\text{ }^{\circ}\text{C}$ and $T_{11} = 200\text{ }^{\circ}\text{C}$). As with the SEM analyses, both 3D surface topographies exhibit continuous feed marks aligned with the end-mill direction, indicating a stable cutting process. However, sample 2 (**Fig. 10a**) shows variations in surface roughness height along the machining grooves, as reflected in the S_a and S_q values. In contrast, sample 11 (**Fig. 10b**) shows a more homogeneous distribution of surface roughness heights (lower peaks and shallower valleys), with reduced S_a and S_q values. These findings corroborate with the 33.3% reduction in R_a and the 25.6% reduction in R_z observed during the 2D characterization. These results indicate that material heating promoted more stable chip formation and reduced the average number of irregularities generated during cutting. However, sample 11 (machined at $200\text{ }^{\circ}\text{C}$) exhibited a significantly higher S_z value than sample 2 (machined at $20\text{ }^{\circ}\text{C}$). This behavior shows that, despite the 3D surface topography having lower average roughness, localized defects can still occur due to discrete adhesion events followed by material pull-out; these events strongly influence the maximum peak-to-valley height without significantly compromising the arithmetical mean height and the root-mean-square height.

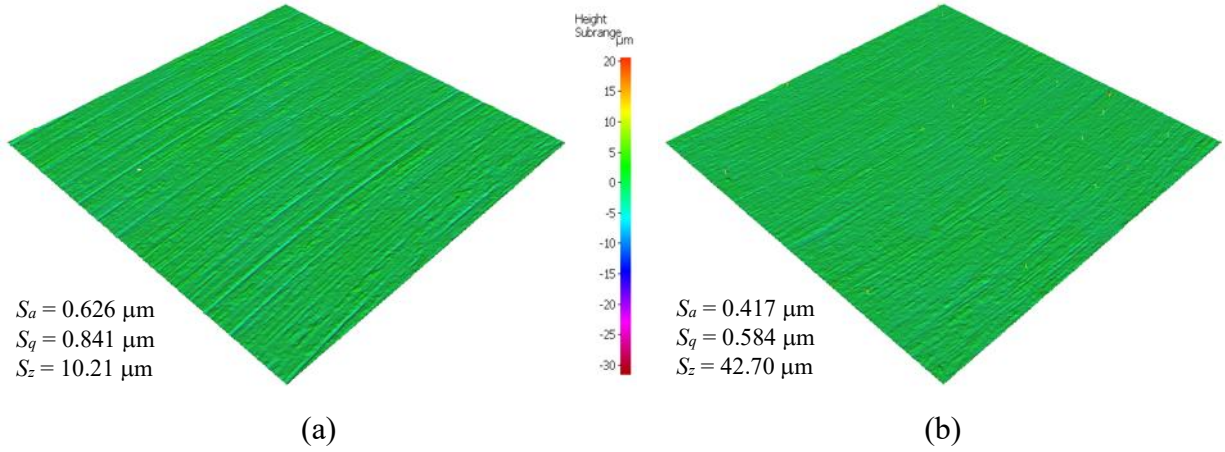


Fig. 10 FVM images of: (a) sample 2; (b) sample 11 (20x magnification)

Fig. 11 compares the FVM images of samples generated using cutting parameter levels from multi-objective optimization: the force-optimized condition ($a_p = 0.2$ mm, $f_z = 0.04$ mm/tooth, $T = 169$ °C) and the roughness-optimized condition ($a_p = 0.5$ mm, $f_z = 0.08$ mm/tooth, $T = 200$ °C). Under the force-optimized condition, the 3D surface (**Fig. 11a**) shows a relatively uniform topography, with continuous machining grooves aligned with the end-mill feed direction. The height distribution is predominantly homogeneous, though some isolated peaks are present (possibly linked to localized adhered material or small chip debris). This characteristic aligns with the S_a and S_q values, which indicate low dispersion in surface heights and confirm that force reduction was achieved without significant deterioration of the surface finish. However, the high S_z value highlights localized, higher-amplitude irregularities (such as debris) that strongly influence this extreme parameter while having limited impact on the average S_a and S_q values. In the roughness-optimized condition, the 3D surface (**Fig. 11b**) exhibits a similarly uniform topography with more regular machining marks and fewer isolated peaks or valleys, indicating a more homogeneous surface across the analyzed area. This condition produced the lowest S_a , S_q , and S_z values among the surface textures in the validation tests, confirming a reduction in both the average surface roughness amplitude and extreme surface irregularities. Although the S_a and S_q values for the two conditions were similar (**Fig. 11a** and **Fig. 11b**), the significant difference in S_z values indicates that the roughness-optimized condition provides better control over localized defects. In contrast, the 3D surface from the force-optimized condition exhibits at least one high peak or deep valley.

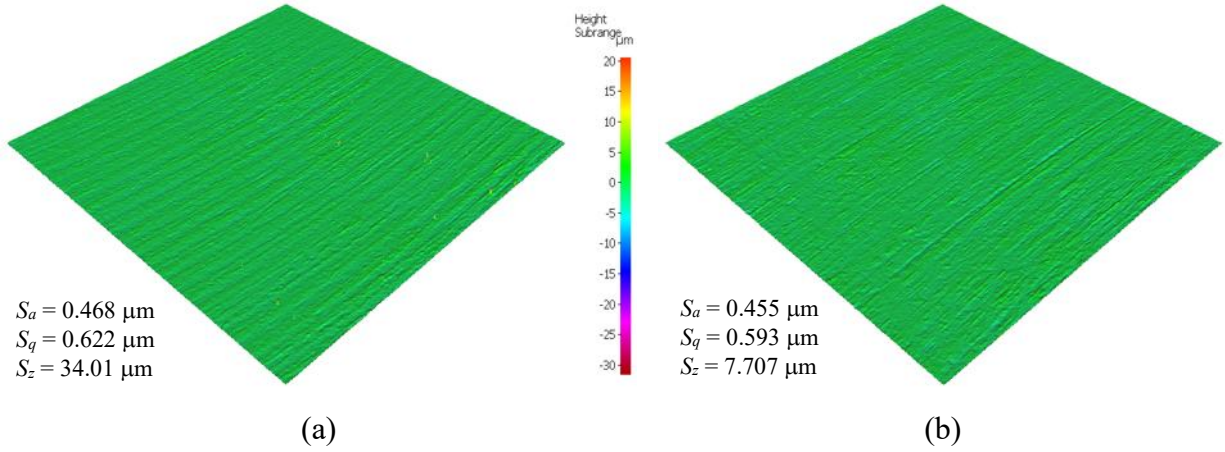


Fig. 11 FVM images (20x) of sample validations for (a) force; (b) roughness

3.3.3 General comments

Scanning electron microscopy (SEM) and focus variation microscopy (FVM) techniques can provide complementary data on surface integrity. SEM images at 150x magnification clearly showed machined surface textures, including smearing, chip debris, and small voids. In contrast, FVM images at 20x magnification covered a significantly larger surface area, which unfortunately reduced spatial resolution. Consequently, small voids observed on surfaces machined under high material heating were not clearly displayed in FVM images. Conversely, FVM more faithfully represented larger-scale topographical variations, allowing clear visualization of machining grooves and effects caused by adhered material, as well as quantification of surface roughness height distribution via S_a , S_q , and S_z parameters. In this study, sample 7 had the highest S_a and S_q values, confirming greater dispersion of surface heights. However, S_z showed high values in some low-roughness situations, such as samples 11 and 12, due to its high sensitivity to isolated peaks and valleys, mainly associated with adhered material. Therefore, S_a and S_q parameters proved to be more representative of the average surface texture, while S_z complemented the analysis by highlighting localized irregularities. Thus, the combined use of these two techniques enabled a more comprehensive assessment of surface integrity, reconciling micrometric-scale morphological information with the quantitative characterization of 3D surface topography.

4 Conclusions

This study assessed the influence of axial depth of cut (a_p), feed per tooth (f_z), and heating

temperature (T) on the machining forces (static and dynamic) and surface roughness (average roughness and mean peak-to-valley height) resulting from end milling of 254 SMO super austenitic stainless steel, employing the 3-factor, 3-level Box-Behnken Design. Based on the results obtained, the following conclusions can be drawn:

- The parameter a_p was the most determining factor on static force (μF_U). An increase in μF_U was directly associated with growth in a_p , especially when combined with high f_z .
- The f_z had the greatest effect on dynamic force (ΔF_U). High f_z intensified force fluctuations, while low f_z might be associated with the plowing effect in the cutting wedge, which can increase specific cutting pressure and, consequently, the force amplitude.
- The quadratic effect of f_z was the most significant factor over the average roughness (R_a) and mean peak-to-valley height (R_z) values. Middle f_z favored a smooth surface finish. A rough surface finish could be related to plowing effect (low f_z) or to feed marks and force fluctuations (high f_z).
- Heating temperature (T) alone did not have a statistically significant effect on machining forces and surface roughness. However, high T reduced both force and roughness values when associated with middle f_z . In contrast, at low f_z , the plowing effect was intensified at high T , thereby increasing the material's thermal softening in the cutting wedge and damaging the surface finish.
- The force values generated by the multi-objective optimization model A ($\mu F_U = 83$ N and $\Delta F_U = 42$ N) were very consistent with the values obtained in the validation tests with the optimized parameters ($a_p = 0.2$ mm, $f_z = 0.04$ mm/tooth, and $T = 169$ °C).
- The multi-objective optimization model B produced roughness values ($R_a = 0.16$ μ m and $R_z = 1.26$ μ m) in very good agreement with the values obtained in the validation tests using the optimized parameters ($a_p = 0.5$ mm, $f_z = 0.08$ mm/tooth, and $T = 200$ °C). Furthermore, the optimized solution achieved a higher material removal rate (2546 mm³/min) than the run producing the sample with the lowest roughness (764 mm³/min), without compromising the surface finish, thereby representing significant gains in process efficiency.
- SEM and FVM analyses corroborated the statistical and roughness results. SEM images showed that the best surface quality among the machined samples was associated with more homogeneous feed marks, reduced material adhesion, less chip debris, and minimal smearing. In contrast, the worst surface roughness exhibited pronounced plowing (reduced feed per tooth

relative to the cutting-edge radius) and adhesion-related defects. FVM images confirmed these observations, with samples showing lower S_a and S_q values under the optimized cutting conditions, while S_z was more sensitive to isolated peaks and valleys (adhered material and small voids, respectively). Furthermore, comparing 254 SMO samples machining at 20 °C and 200 °C indicated that thermally assisted end milling promotes a more uniform surface texture and reduces average height parameters, although localized micro-defects may still remain.

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7 Credit authorship contribution statement

- **Émerson S. Passari:** Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Visualization, Writing – original draft, Writing – review & editing.
- **André J. Souza:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing.
- **Carlos A. G. Aita:** Methodology, Investigation, Validation, Writing – review & editing.
- **Guilherme V. Schirmer:** Investigation, Data curation, Writing – review & editing.
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8 Competing Interests: Statements and Declarations

No potential conflict of interest was reported by the authors.

9 Declaration of generative ai and ai-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used ChatGPT (OpenAI) to assist with textual orthographic and grammatical editing and to aid the organization and refinement of some parts of the manuscript. After using this tool, the authors take full responsibility for the content of the published paper.

10 Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

11 Ethical standards

The manuscript does not contain clinical studies or patient data.

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