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Effect of cutting parameters and CO_2 flow rate on surface integrity in milling AISI 316L steel using supercritical CO_2

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Abstract

The machining challenges commonly experienced in the milling of stainless steels, such as the formation of built-up material on the cutting tool edge and the low thermal conductivity resulting in high heat generation within the cutting zone, require the application of a lubricating cutting fluid. Manufacturing industry traditionally uses an oil-based coolant for dissipating frictional heat and reducing chip adhesion to the cutting tool; however, this is not environmentally sustainable. In this study, a design of experiment (DoE) approach was employed to investigate the impact of feed per tooth, cutting speed, and the flow rate of supercritical carbon dioxide ($scCO_2$) on cutting forces and surface integrity during face milling of AISI 316L. As expected, it was observed that surface residual stresses increased with an increase in the feed rate. The surface roughness remained unaffected by changes in $scCO_2$ flow rate and variations within the range of machining parameters considered in the experimental design. $ScCO_2$ demonstrated its potential as a sustainable coolant substitute in the industrial machining of austenitic stainless steels.

Keywords: Supercritical carbon dioxide; machining; stainless steel, surface integrity

1. Introduction

Stainless steel AISI 316L is a commonly used material in various industries where a good resistance to corrosion is required. The challenges experienced when machining austenitic stainless steels can primarily be attributed to their high ductility and low thermal conductivity, resulting in elevated temperatures during machining processes and material accumulation on the cutting tool's edge [1].

Strain-induced martensite is common in stainless steels processed using equal channel angular pressing or shot peening. In machining, the substantial increase in temperature inhibits martensite formation as observed by Wu et al. [2]. However, strain rate sensitivity affects strain hardening at higher cutting speeds, resulting in a significant increase in cutting forces and residual strain, leading to high tensile surface residual stress. This is recognised as one of the factors contributing to stress-corrosion cracking [3], [4].

Conventional machining processes use water-soluble cutting fluids, often referred to as 'flood coolant'. In the pursuit of more sustainable manufacturing techniques, Maurotto et al. [5] conducted a study aimed at characterising the response of AISI 316L to abusive dry-milling conditions, utilising an extended range of cutting parameters and a DoE approach. Dry machining, however, despite eliminating the need for cutting fluid disposal and post-machining component cleaning processes, can adversely impact the machinability of 316L stainless steel, compromise machined surface integrity, and reduce tool life due to increased friction and temperature.

These challenges have encouraged the exploration of alternative coolant techniques to address the environmental concerns associated with conventional coolants. Sustainable coolants, such as $scCO_2$, help reduce dependency on conventional coolants and mitigate their associated drawbacks. Wika et al. [6], demonstrated the benefits of $scCO_2$ with Minimum Quantity Lubrication (MQL) in their study on AISI

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304L steel during face milling. They observed a significant increase in tool life when using $scCO_2$+MQL compared to conventional cutting fluids, along with a reduction in surface roughness and no significant difference in surface residual stresses. These experiments increased confidence in the suitability of $scCO_2$ as a traditional coolant substitute.

This study aims to explore the influence of cutting parameters and $scCO_2$ flow rate on surface integrity when face milling AISI 316L stainless steel. The methodology developed for machining with $scCO_2$, as presented in this paper, was further improved for use in machining 316L stainless steel to investigate the impact of surface machining on environmentally assisted cracking (EAC) in light water nuclear reactor environments. Findings reported by Zimina et al. [7] highlighted that advanced surface machining with $scCO_2$ revealed a comparable EAC initiation behaviour to the standard machining method, demonstrating that this approach is not inferior to conventional methods. Considering advantages such as higher cutting speed and reduced pollution, $scCO_2$ appears to be a promising alternative to conventional coolants when machining steels.

Nomenclature

a_p	Axial depth of cut, mm
a_e	Radial depth of cut, mm
f_z	Feed rate, mm/tooth
V_c	Cutting speed, m/min
$scCO_2$	Supercritical carbon dioxide
MQL	Minimum quantity lubrication
DoE	Design of experiments
CCF	Central composite design
DoF	Degrees of freedom
Q^2	Measure of predictive ability
R^2	Measure of fit
Ra	Arithmetical mean surface roughness value, µm
RSD	Residual Standard Deviation
XRD	X-Ray Diffraction

2. Experimental work

The machining trials were conducted using a 4-axis Starrag Heckert 1800 machining centre, retrofitted with an $scCO_2$ unit manufactured by Fusion Coolant Systems Inc. This unit delivers a controlled stream of $scCO_2$, either with or without minimum quantity lubrication (MQL). For the entire experiment, the selected cutting tool was a Ø42 mm 419 series face mill (419-042C4-14M) mounted on a C4-390.410-100 090A adaptor. The tool was used with three indexable cutting inserts suitable for stainless steels, specifically, type 419R-1405E-MM carbide grade 2040, coated with TiCrN+AL_2O_3+TiN.

To establish the relationship between process input parameters (feed per tooth, cutting speed, and coolant nozzle diameter) and outputs (such as surface roughness and near-surface residual stresses), a DoE statistical approach was employed. A central composite face (CCF) design was selected, consisting of a full factorial design and star points positioned at the centre of each face (of each side).

The $scCO_2$ was mixed with 1 ml/min of NuCut Plus MQL oil. Three different coolant nozzle diameters were used, which, at the operating pressure of 13.8 MPa (138 bar) $scCO_2$, resulted in the $scCO_2$ flow rates as shown in Table 1.

Table 1. Coolant nozzle diameters and corresponding $scCO_2$ flow rates.

Nozzle diameter [mm]	Operating pressure [MPa]	$scCO_2$ flow rate [kg/h]
0.15	13.8	14.4
0.20	13.8	27.7
0.25	13.8	39.2

The study consisted of two stages: Stage 1, which focused on screening cutting process input parameters, with optimisation trials in Stage 2. Residual stresses were determined using a laboratory based Proto LXRD residual stress measurement unit, using unfiltered Mn K-alpha radiation at multiple inclination angles (φ). Surface roughness, including the arithmetical mean deviation of the profile (Ra), was measured using a portable surface roughness tester Mitutoyo Surftest SJ-410 (cut-off value of 2.5 mm). Cutting forces were measured using a custom-built Kistler 9366C dynamometer with a force plate measuring 500 x 500 mm.

2.1. Design of Experiments (Stage 1 - screening trials)

Two AISI 316L stainless steel plates (250 x 200 x 15 mm) were used in the screening experiments. A total of eighteen runs were carried out following a randomised run order, which included fourteen runs in a quadratic model design and four centre points. During each climb milling pass, a radial depth of cut (a_e) of 26.56 mm (corresponding to 80% of the tool effective diameter of 33.2 mm) and a fixed axial depth of cut (a_p) of 1 mm were consistently maintained. The plates were securely fastened in the Hilma NC160 vice, which was vertically fixed to a tombstone block (Figure 1).

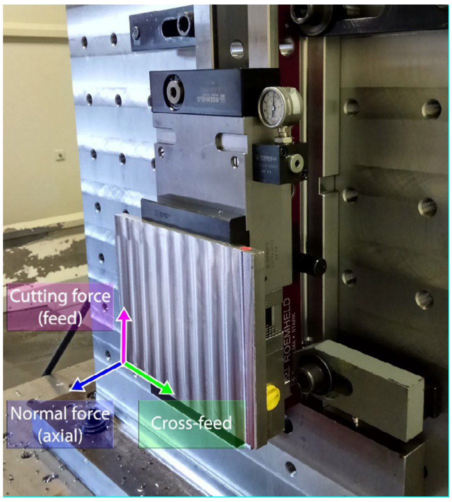

Fig. 1. Experiment setup for flood coolant and $scCO_2$ DoE Stage 1 on the Starrag HEC1800.

Each plate allowed for nine passes. The factors and their corresponding levels used in the DoE design are detailed in Table 2.

Table 2. Factors and their corresponding levels (DoE Stage 1).

Factor	Feed per tooth f_z [mm/tooth]	Cutting speed V_c [m/min]	Nozzle diameter [mm]
Low level	0.4	210	0.15
Medium level	0.8	235	0.20
High level	1.2	260	0.25

2.2. Design of Experiments (Stage 2 - optimisation trials)

Following DoE Stage 1, additional cutting trials were conducted on a 300 x 150 x 50 mm AISI 316L plate (Figure 2).

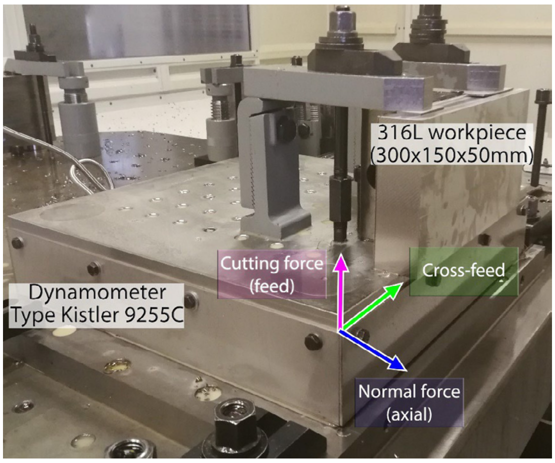

Fig. 2. Experiment setup for flood coolant and $scCO_2$ DoE Stage 2 on the Starrag HEC1800.

Two sets of DoE trials were undertaken to expand and optimise the design space, including an expanded range of feed per tooth, as detailed in Table 3 and Table 4.

Table 3. Cutting conditions for investigating the relationship between feed per tooth and $scCO_2$ flow rate (14.4 kg/h to 27.75 kg/h).

Factor	Feed per tooth f_z [mm/tooth]	Nozzle diameter [mm]
Low level	0.2	0.15
High level	0.6	0.20

Table 4. Cutting conditions for investigating the relationship between feed per tooth and $scCO_2$ flow rate (27.75 kg/h to 39.2 kg/h).

Factor	Feed per tooth f_z [mm/tooth]	Nozzle diameter [mm]
Low level	1.0	0.20
High level	1.4	0.25

A full factorial two-level design, consisting of four runs, was repeated three times, resulting in a total of twelve runs. The cutting speed was maintained at a constant value of 210 m/min. Each pass was carried out with an engagement width a_e of 23.24 mm (corresponding to 70% of the tool effective diameter of 33.2 mm) and a depth of cut a_p of 1 mm. After the initial set of passes, the plate was rotated by 180°, and the other side was used for the second half of the DoE trials, involving both flood coolant and $scCO_2$. In total, twenty-four passes were completed, with twelve passes on each side of the plate for the second stage of the DoE design.

3. Results and discussion - DoE trials Stage 1

3.1 Residual stress

Figures 3 and 4 present the regression coefficients of the residual stress model. The feed per tooth factor had the strongest positive effect on the response variable (residual stress). This suggests that an increase in feed per tooth leads to higher residual stress.

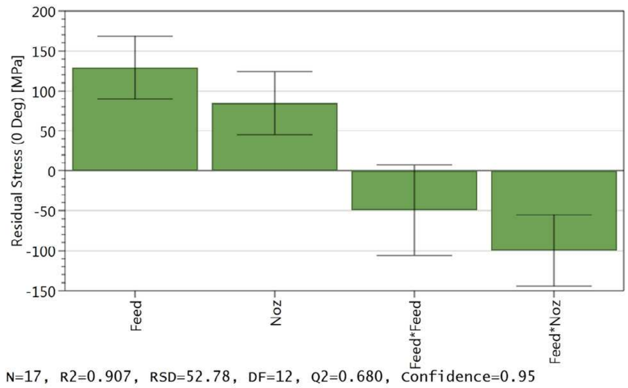

Fig. 3. Regression coefficient plot: influence of feed per tooth, nozzle diameter, and interactions on transverse residual stress (φ = 0°).

The increase in material removal rate, results in raised temperatures and increased strain within the cutting zone. This contributes to increased tensile residual stress, a phenomenon commonly observed in the machining of low-alloyed steels, as supported by prior studies, such as those conducted by Maurotto et al. [5].

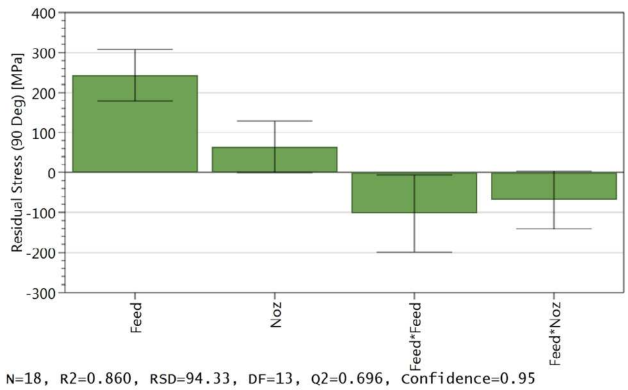

Fig. 4. Regression coefficient plot: influence of feed per tooth, nozzle diameter, and interactions on longitudinal residual stress (φ = 90°).

It was observed that the modest increase in cutting speed was not a significant factor within the investigated design space, ranging from 210 to 260 m/min. Consequently, cutting speed was excluded from the residual stress model.

Figure 5 shows the interaction plot between feed per tooth and nozzle diameter concerning surface residual stresses. In both transverse and longitudinal directions, the influence of feed per tooth was particularly evident for small nozzle diameter, i.e., with a low $scCO_2$ flow rate. Conversely, for a high $scCO_2$ flow rate (indicative of a high level of cooling) other mechanisms occur, specifically increased heat transfer and plastic deformation, leading to the development of higher tensile stresses. Rapid cooling can induce a quenching effect, where the material cools too quickly, resulting in increased hardness and higher residual stresses. The values ranged from approximately 820 MPa for a feed rate of 0.4 mm per tooth to as much as ~1270 MPa for a feed rate of 1.2 mm per tooth.

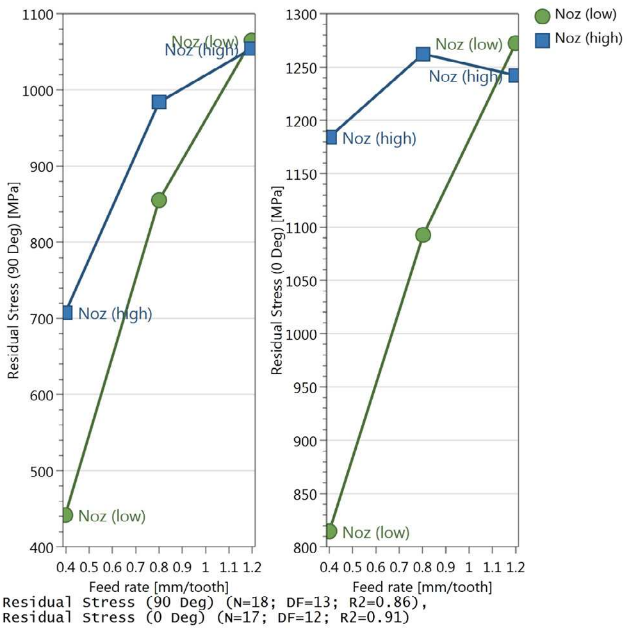

Fig. 5. Interaction between feed per tooth and nozzle diameter for longitudinal (left) and transverse (right) residual stress.

Figure 6 shows a 2D response surface contour plot for the mean residual stress, showing predicted response values based on two factors: feed per tooth and nozzle diameter.

At higher feed per tooth, nozzle diameter had no impact on residual stress levels, possibly due to reaching the maximum cooling potential and being unable to counter the rapid generation of heat during the process. Transverse residual stresses in milling of 316L stainless steel are typically significantly higher than longitudinal residual stresses due to the deformation caused by the cutting tool.

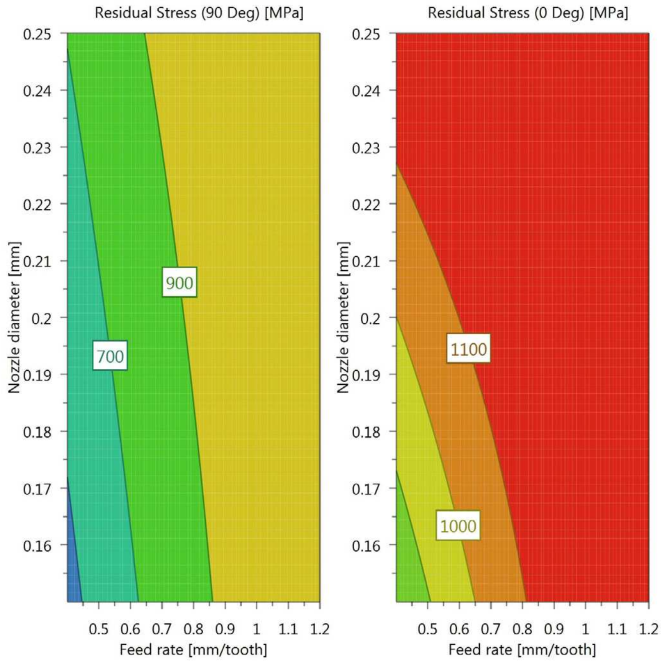

Fig. 6. A response contour plot of mean residual stresses (relationship between feed per tooth and nozzle diameter).

3.2 *Surface roughness*

A statistically significant model (at 95% confidence level) could not be built due to the statistical effect of feed per tooth, cutting speed, and nozzle diameter on surface roughness (Ra) falling below the experimental noise. The most substantial variation in surface roughness was observed between a feed per tooth of 0.4 [mm/tooth] (Ra = 0.8 µm) and one of 0.8 [mm/tooth] (Ra = 1.6 µm). Furthermore, the influence of $scCO_2$ flow rate on surface roughness was minimal, with no significant effects observed. Even though the cutting tool used in the experiments was a high-feed cutter typically used in roughing machining operations, the resulting Ra values remained relatively low. This suggests that other factors, such as tool wear, may play a more important role in determining the final surface quality.

Furthermore, nozzle diameter did not appear to significantly affect linear surface roughness. This observation implies that chip removal during the machining process was primarily achieved through mechanical means, with the expansion of gas playing a limited, if any, beneficial role.

Higher-than-expected levels of noise made it challenging to identify trends in skewness and kurtosis for both linear and areal parameters. In general, however, the effects of $scCO_2$ flow on surface roughness appeared to be limited and somewhat similar to the effects observed in the analysis of residual stresses. Larger nozzle diameters had a detrimental impact in both cases, although the magnitude of this effect was relatively small compared to the variations caused by changes in feed per tooth.

4. Results and discussion – DoE trials Stage 2

Plotting the raw data from the two DoE trials in Stage 2 was preferred, rather than using the statistical models, in order to display a more visually apparent trend and identify the influence of feed per tooth on cutting forces, surface residual stress and surface roughness.

3.3 Cutting forces

Figure 7 shows a similar trend to that observed in the residual stress data: an increase in feed per tooth corresponds to higher cutting forces.

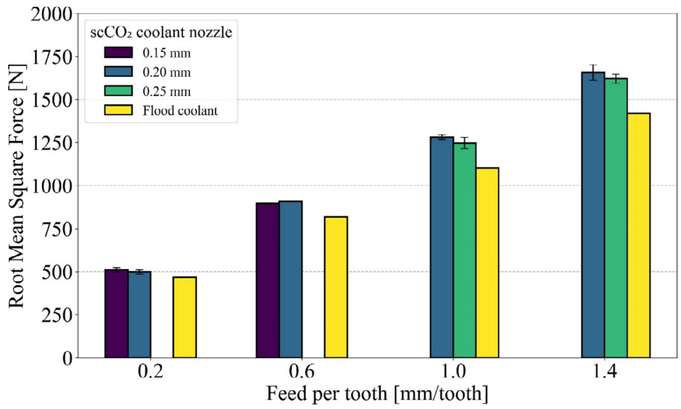

Fig. 7. Root mean square of cutting forces in relation to feed per tooth.

The increased cutting forces observed with $scCO_2$+MQL, as opposed to flood coolant, can be attributed to the temperature gradient in the cutting zone, which impacts the ductility of the material. $ScCO_2$ dissipates heat much more efficiently than flood coolant, resulting in a reduced localised temperature and reduced ductility. This, in turn, leads to higher resistance to cutting, raising the cutting forces imposed on the cutting tool. This becomes particularly relevant when machining at high feed rates, where frictional forces can have a significant impact on tool wear and the overall efficiency of the machining process.

4.1 Residual stress

Figure 8 and Figure 9 show the measured data for transverse and longitudinal residual stress, respectively, along with their variations with increasing feed per tooth.

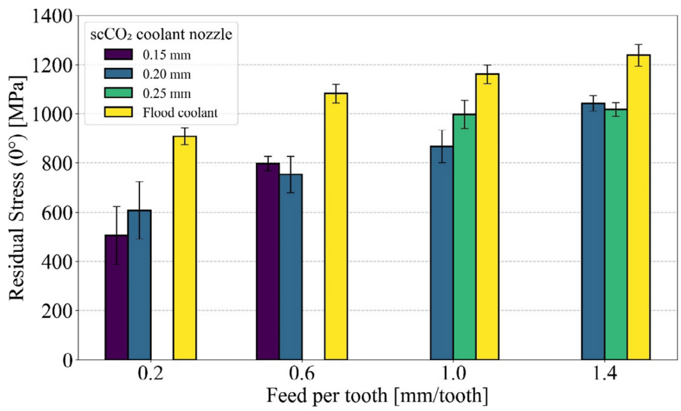

Fig. 8. Residual stress in transverse direction (ϕ = 0°), with changes in feed per tooth and nozzle diameter.

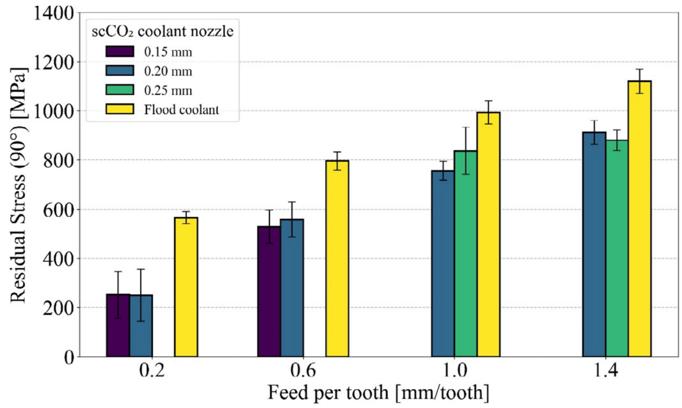

Fig. 9. Residual stress in longitudinal direction (ϕ = 90°), with changes in feed per tooth and nozzle diameter.

The results obtained with flood coolant are included for reference. The observed increase in residual stress at higher feed per tooth rates can be attributed to several factors. At higher feed rates, there is an increased amount of heat being generated due to higher material removal rates. The excess heat can lead to localised thermal expansion in the workpiece, resulting in the locking of residual stresses. Additionally, higher feed rates often result in more aggressive cutting conditions, including increased cutting forces (as seen in the root mean square force in Figure 7) and increased mechanical deformation of the workpiece.

The levels of residual stress observed with $scCO_2$ are lower compared to those with flood coolant. This difference can be attributed to the efficient dissipation of heat from the cutting zone, thus minimising the thermal effects contributing to the formation of residual stress.

It was observed that, at a particular feed per tooth value, nozzle diameter had no statistically significant impact on residual stress levels in both the transverse and longitudinal directions within these design space regions. An evident trend was noticed, suggesting that high feed rates led to increased residual stresses in both directions, regardless of the cooling method used.

4.2 Surface roughness

Figure 10 summarises the Ra values for each cooling method at specific feed per tooth settings. Similar to the findings in Stage 1, a statistical model for surface roughness could not be developed due to the limited impact of feed per tooth and nozzle diameter on this parameter.

The influence of $scCO_2$ flow rate on surface roughness was found to be limited, with no statistically significant effects observed when comparing nozzle diameters of 0.15 mm, 0.20 mm, and 0.25 mm. The lowest Ra value was measured using $scCO_2$+MQL cooling with a feed per tooth of 0.20 [mm/tooth], while the highest Ra values ($scCO_2$+MQL) were associated with feed of 1 mm/tooth and 1.4 mm/tooth.

At a low feed per tooth of 0.2 mm/tooth, surface roughness with flood coolant was only marginally higher than that with $scCO_2$+MQL. This difference became more pronounced as the feed per tooth increased to 0.6 mm/tooth, resulting in the highest surface roughness observed in this experiment, averaging around Ra = 2 µm. However, further increases in feed rate did not significantly alter surface roughness values, as the results remained consistent regardless of the cooling method used. The considered machining parameters had limited influence on surface roughness within the specified range.

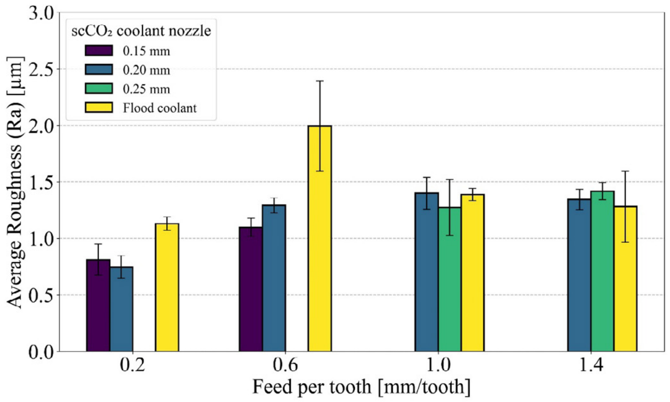

Fig. 10. Surface roughness in relation to feed per tooth and coolant nozzle diameter.

5. Conclusions

In this study, experiments were carried out to investigate the impact of cutting parameters (namely, cutting speed and feed per tooth) and the flow rate of $scCO_2$+MQL on surface integrity during the milling of 316L stainless steel. The research findings revealed that both transverse and longitudinal surface residual stresses increased with higher feed rates, while cutting speed had a minimal effect. Feed per tooth emerged as the most influential parameter affecting residual stress. Flow rate, varying with the nozzle diameter, also had an impact, albeit to a lesser degree.

Furthermore, the analysis of surface roughness indicated that feed per tooth played a role in determining surface quality. Flow rate, varying with the nozzle diameter, and cutting speed had negligible effect on surface roughness, suggesting that mechanical chip removal played a dominant role. As expected, cutting forces increased with higher values of feed per tooth.

These findings contribute to provide a better understanding of the relationships between machining parameters and surface integrity when utilising $scCO_2$+MQL as a coolant and lubricant.

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