Investigation into the surface quality and stress corrosion cracking resistance of AISI 316L stainless steel via precision end-milling operation

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Abstract
This study presents a two-fold investigation on precision end-milling of stainless steel (AISI 316L). First, the impact of end-milling variables (cutting speed and feed rate) on the surface quality (surface roughness, microhardness, and surface morphology) was analyzed. The best surface quality with surface roughness ($R_a$) 0.65 ± 0.02 μm was observed for cutting speed of 140 m/min and 0.025 mm/tooth of feed rate. Microhardness was increased with increment in cutting speed. Second, the impact of surface roughness ($R_a$) on the stress corrosion cracking under two different mediums, i.e., body solutions (Hank’s solution) and 1 M hydrochloric acid solution, was studied. The investigations showed that the samples with higher surface roughness values were more prone to stress corrosion cracking.

Keywords Precision end-milling · Surface roughness · Stress corrosion cracking · Surface integrity

1 Introduction
Austenitic stainless steel is famous for its high corrosion-resistant properties, excellent mechanical strength, low thermal expansion, low cost, and good reliability [1, 2]. It is applied in chemical, aerospace, power plants, and biomedical industries for years now. It is also one of the most used materials in biomedical applications especially in the forms of implants for the human body. AISI 316L is one of those materials [3]. It is recommended as a biomaterial because the presence of low carbon content improved its corrosion resistance against chlorinated environment, similar to the human body environment which contains saline solution [4]. AISI 316L is often considered as a “difficult-to-machine” material. The reason behind this could be elevated “ductility”, higher “tensile strength”, and poor “thermal conductivity”. All these things collectively produce an unacceptable surface finish and also shortened the tool life due to rapid tool wear [5, 6]. Apart from that, high fracture toughness of AISI 316L increases the temperature in the primary cutting zone which deteriorates the surface finish and the ability of the chip to break. Moreover, the “built-up-edge” (BUE) generation is also significantly found at high cutting speeds which also deteriorate the surface quality which in turn increases the cutting forces during machining processes [7]. During machining, the resultant surface finish ranks first among the most demanded customer...
requirements where a substantial symptom of surface finish on machined products is the roughness index [8]. For obtaining high integrity, the surface roughness index should be minimum level. The work material surface roughness is greatly impressed by actual cutting parameters, i.e., “feed rate, cutting speed, and radial and axial depth of cut”, besides the non-controlled agents, namely non-uniformity of work material and the cutting insert [9, 10].

Presently, the practice of high-speed machining (HSM) gets a good reputation in the modern manufacturing due to its cost-effective property, improved machining performance, less lead time, and enhanced productivity [11]. The quality of the product, made of 316L SS, depends on the surface integrity changes that occurred during the machining. There are various machining techniques available for the manufacturing of implants from AISI 316L SS that is turning, milling, drilling, shaping, etc. [12]. Nevertheless, the end-milling process is used for 316L SS compression plate machining which is used for the support of broken bones in the body [13]. Surface roughness of 316L SS has a great impact on the corrosion behavior, particularly in the case when it is inserted within the human body. There are chances of various corrosion attacks on the implant which may be “galvanic corrosion”, “stress corrosion cracking” (SCC), “fatigue and pitting” corrosion. Among above-mentioned corrosion types, the possibility of SCC is highest due to the existence of the movement in the joints which produce tensile stress due to mechanical load and the surrounding acidic environment around the implant. SCC is also one of the major causes of the broken implant that produce infection to the healthy cells inside the human body. The severity of the stress corrosion cracking leads to the operation procedure for the person in order to take out the broken implant.

It is appreciable that surface roughness has clear effect on the SCC initiation. The rough surface has deep grooves on which the aggressive species concentrate. These grooves help to increase the stress which reduces the development time to cause the SCC. It can be seen that in the case of SCC in chloride environment, the growth of chloride ions and the resultant destruction of the passive film is more if there exist deep grooves on the surface [14, 15]. It has been shown that the right combination of cutting parameters can increase the durability of the 316L as it can reduce the chemical reactivity and susceptibility to SCC [16]. Khleif et al. [9] worked the impact of machining variables such as the speed of cutting on AISI 316L surface condition and tool wears during milling operation. It was reported that the enhancements in the spindle speed decrease the surface roughness but increase tool wear. For selected machining variables, the roughness level \((R_s)\) increases from 1.526 to 2.648 \(\mu m\) with deterioration in flank wear from 0.31 to 0.41 \(mm\). Lin et al. [17] worked on the optimization technique to develop the surface finish along with the amount of material cutting and reduction of burr height. After evaluating the surface roughness and burr height for optimization, they reached to the conclusion that feed rate stood as the most influential criterion on roughness. A similar conclusion was reported by Asilturk and Akkus [18]; however, the work material was AISI 4040 steel. That the hard materials like 316L SS to be machined through HSM and the impression of operating parameters on their machinability needs to be defined. Zafer et al. [19] explored the impression of machining parameters while turning AISI304. The best surface with regard to roughness was reached at 150 m/min cutting speed and feed rate of 0.25 mm/rev. Machining of other steels, like the AISI 1040, was studied using “response surface methodology” (RSM) to find that tool wear and total machining time influence the surface roughness [20–22]. Baek et al. [23] performed face milling on AISI 1041. They focus on the dependence of the surface roughness and “material removal rate” (MRR) on the feed rate. They stated that the modeling and optimization of the process can be valuable for determining the best surface finish. Stoic et al. [24] explored the machining condition of hard mold steel for the high-speed turning process and claimed that machinability was addicted to the machining parameters and tool wear. Ryu et al. [25] investigated the end-milling process and the surfaces generated as a result of this process. According to their results, cutting insert geometry and surface cutting cases impact the surface texture. Davim and Figueira [26] implemented an orthogonal array for the analysis of tool steel D2 (AISI) with action of machining variables on the surface integrity. Their outcomes proved that the best surface quality with \(R_s = 0.8 \mu m\) may reduce the extra grinding operation required as post machining operations. Jasni et al. [27] surveyed the variations that occur in the surface roughness level of type-D2 steel via dry machining. They found that as per the topography analysis, the machined surface is anisotropic in nature. Furthermore, the unacceptable quality of the surface was observed with the decreased cutting speed along with the higher radial depth of cut. Chang et al. [28] examined the relationship of operating variables on SCC of heat-treated AISI 316L. From their results, it was found that the cracks are only initiated when the machining marks are at 90° with respect to the force applied on the sample. These marks produced oxide layer on the inner side of the sample that is the cause of the crack initiation. Zhang et al. [29] investigated the effects of cutting-induced surface residual stress on the induction of SCC in the processing of AISI 316 material. The results proved that the stress corrosion cracking is obvious when the machined surface having higher amount of tensile residual stress.

Although in some conditions where the surface roughness value is the same for the material specimen after the cutting process, they show different resistance to the SCC. It is due to the difference in the irregularities in the sub-surface of the specimen [30]. The relative movement of the joints with fixed implants having high surface roughness produces corrosion.
Sometimes, the tiny particles from the corroded implants leached into the main blood stream subsequently, changes the blood pH. These corroded particles are being absorbed by the bones which alter the composition of the bone that reduces its strength. Improper diagnosis sometimes leads to necrosis or osteoporosis which is the perpetual destruction of the bone’s tissue. The implant degrades in a slow manner and the degradation is solely dependent on the surface roughness pattern [31]. For that purpose, the surface morphology deserves intensive attention as a subject of research in the biomedical and manufacturing domain.

For SCC to occur, a crack commences at the surface of the specimen at the point where it interconnects with the environment. Hence, it is critical to survey the effect of machining process on surface roughness and its relation to SCC initiation in 316L SS used as material for body implants. It will develop appropriate machining practices for safe integration in the human body and extended service life. The present study has two-step objectives. At first, a precision end-milling operation was performed on the 316L steel. The dependence of surface integrity (roughness, surface morphology, and hardness) on the cutting parameters was investigated. After that, SCC of 316L under two different environments (i.e., Hank’s solution and HCl solution) was studied for samples having different surface quality.

2 Experimental method

2.1 Material and machining procedure

The specimen of AISI 316L steel in the plate form with 12.5 ± 0.2 mm thickness was employed in the current work. The weight % of the elements present in the 316L SS is given in Table 1.

A five-axis machine Mazak Variaxis (630-5×), eligible to perform high-speed end-milling, was utilized to be carried out in the experiments. The procedure of the precision process is presented in Fig. 1. The machining process was initiated using uncoated tungsten carbide tool (Portray Co. Ltd) with a diameter of 5 ± 0.01 mm having four flutes. The flute length was 14 mm with an overall length of 50 mm.

The end-milling was performed at various cutting speeds (80 to 140 m/min) with a constant 0.3 mm axial and 5 mm radial depth of cut. In addition, four feed rates viz., 0.025, 0.03, 0.035, 0.04 mm/tooth were practiced. Each machining experiment is repeated three times.

2.2 Surface characterization

The “Mitutoyo SV-3000” profilometer was used to measure the surface roughness. The sampling length for each measurement was 50 mm, and every measurement reported for an average value of three scans for identical locations to obtain mean surface roughness as Ra. The resolution on the X-axis resolution was 0.05 μm and Y-axis 1 μm, respectively. Moreover, the surface topography and more in-depth details of the surface roughness were studied using 2D laser scanning microscope (Sensofar, Barcelona, Spain). Furthermore, the microscopic data was sorted and fitted using a Gaussian filter. To achieve that, square samples each of 3508.8 μm were taken out from the 316L SS, using the “wire electro-discharge machine” (WEDM) process to appraise the changes when end-milling process and to investigate the surface roughening behavior of the sample.

2.3 Stress corrosion cracking

The stress corrosion cracking (SCC) susceptibility was investigated by following the ASTM G30 standard, in which a constant strain was applied to each sample using a bender and converted to U-shaped bent samples as displayed in Fig. 2. The machined surfaces having varying Ra values were subjected to tensile stress were immersed in Hank’s solution (Table 2) and in the 1 M HCl solution for the total duration of 8 weeks. The samples were carefully examined after a regular interval of time, i.e., 24 h, 2 weeks, 4 weeks, and 8 weeks, respectively. In these 8 weeks, the specimen was taken out after every 24 h, washed with distilled water, dried with acetone, and examined under a microscope for surface crack analysis. The crack density was analyzed using Matlab 9.3. However, high-resolution electron microscope (FESEM)

Table 1 Composition of AISI 316L [28]

| C   | Mn | P  | S  | Si | Cr | Ni | Mo | Fe  |
|-----|----|----|----|----|----|----|----|-----|
| 0.03| 1.9| 0.2| 0.03| 0.75| 14.5| 9.1| 2.8| Bal |
(Ziess Supra 55VP) was used to characterize the morphology of machined surface.

3 Results and discussion

3.1 Surface roughness

In this section, the influence of the cutting speed \( (V_c) \) at a constant feed rate \( (f) \) on average surface roughness \( (R_a) \) is provided in Fig. 3. It can be monitored that irrespective of feed rate, an increment in machining speed caused the surface roughness to be decreased, even below 1.0 \( \mu m \)—a testament of precision milling. The cutting speed in the range 120–140 m/min was found to be acted as a beneficiary range of machining. It can be noted that higher cutting speed bolsters a higher material removal rate, namely improved productivity. Quantitatively to say, at 80 m/min cutting speed, the surface roughness had the value of \( R_a = 2.39 \mu m \). It is obtained that least surface roughness with 0.65 \( \mu m \) was formed at the optimum \( V_c \) of 140 m/min and \( f \) of 0.025 mm/tooth. The increment in the \( V_c \) reduced the time of machining which reduces the BUE formation and the chip breakage. Moreover, the small contact time of broken chips with 316L SS resulted in reduced heat transfer from the chip to workpiece leading to minimized surface roughness \([32, 33]\).

Moreover, the relationship of the surface roughness with feed rate at several cutting speeds is also provided in Fig. 3. It is quite obvious that an increment in feed rate (irrespective of cutting speed) triggered the deterioration in surface quality. The similar results were reported by Gupte et al. \([34, 35]\) while turning titanium alloy. For instance, when the machining was run at \( V_c \) of 80 m/min, the lowest \( f \), i.e., 0.025 mm/tooth generated the minimum surface roughness value of \( R_a = 2.39 \pm 0.4 \mu m \). However, when this feed rate was raised continually, the surface roughness increased to \( 3.12 \pm 0.45 \mu m \). When machining process, the temperature in the primary zone of the machining mechanic is high near the tool edge which is around 750 to 900 °C. When the \( f \) rise to 0.04 from 0.025 mm/tooth, the material removal rate is also increased which raised the machining zone temperature, and consequently, high energy is required to remove the material. This increased temperature favors plastic deformation which are commonly tensile and compressive in nature. The deformation that occurs under the insert flank surface is the tensile plastic deformation and that ahead of the tool is compressive deformation \([36]\). When the feed rate is high, it resulted in serious inhomogeneous

| Substance composition | g/L  |
|-----------------------|------|
| NaCl                  | 0.8  |
| KCl                   | 0.4  |
| NaHCO₃                | 0.35 |
| NaH₂PO₄·H₂O          | 0.25 |
| Na₂HPO₄·2H₂O         | 0.06 |
| CaCl₂·2H₂O           | 0.19 |
| MgCl₂                | 0.19 |
| MgSO₄·7H₂O           | 0.06 |
| Glucose              | 1    |
| pH                   | 6.9  |

Fig. 2 Machined samples a sliced sample after machining, b bending of sample, c bent sample

Fig. 3 Surface roughness variation versus cutting speed and feed rate
corruption across the cutting tool edge which directly resulted in increased surface roughness [37].

As per data, it was detected that the lowest value for surface roughness was captured at the cutting speed of 140 m/min and the feed rate of 0.025 mm/tooth during the end-milling. During machining, as the feed rate rises, the heat is generated between cutting tool and workpiece thereby, dislocating the grain boundaries resulted in escalation of level of surface roughening. Moreover, the tool nose radius is worn out which makes the tool dull and comparatively blunt which deteriorates the surface [38, 39]. Similar trends were highlighted by Zahoor et al. [40] who used the AISI 316L material using end-milling. The average surface roughness parameter $R_a$ was found to be on the lower zone when a high value of the cutting speed and low value of the feed rate were maintained. The overall values of $R_a$ and 3D surface roughness ($S_a$) are given in Table 3.

### 3.2 Surface morphology

Figure 4 shows the surface morphology of machined specimens prepared at high and low cutting speed. It can be seen that indigent surface pattern is obtained in sample machined at less cutting speed on account of the presence of defects such as voids, feed marks, chip formation, and BUE as provided in Fig. 4a. At low cutting speed, the BUE was formed on account of plastic deformation of material [41, 42]. But, as the cutting speed increased, these imperfections and irregularities disappeared and resulted in a smoother surface as illustrated in Fig. 4b. At the greatest cutting speed ($V_c = 140$ m/min), the primary zone temperature was higher in comparison with lower cutting speed; this thermal state decreased the yield strength of material, decreasing the cutting force requirement to machine the material and resulting in a smoother surface. The formation of the BUE at a higher cutting speed was reduced along with the voids which improved the surface quality [43, 44].

Figure 5 shows a 2D surface profile scan of the sample with lowest and highest $Z (\mu m)$ value. It is well known that for the machined surfaces, a correlation among the $R_a$ and the cutting parameters can be better judged based on the 2D surface textures. Figure 5 indicates the 2D roughness profile scan of the specimen using middle ($Y = 1320 \mu m$) over a distance of 3508.8 $\mu m$. As per Fig. 5a, it can be observed that high peaks and deep valleys parallel to rotation axis of the cutting tool on the surface which is identified by lower cutting speed and higher feed rate. Moreover, increment in the $V_c$ minimizes the height of those peaks and valley pattern as observed from the Fig. 5. Higher surface roughness is prevalent with elevated feed rate along with the poor cutting speed and it is confirmed by microscopic observations.

Figures 6 and 7 demonstrate 2D surface roughness scan of the sample having different cutting parameters. It was observed that an increase in feed rate at constant cutting speed shows more cutting wear marks with numerous cracks compared with the increase in cutting speed at a fixed feed rate. The higher cutting speed values increase the transfer of heat between tool and workpiece. As a result, the chemical composition is changed and thereby increases the tool wear values. When machining process, the resulted chip from work-material slides over the tool surface. Consequently, few

| Test No. | Cutting speed (m/min) | Feed rate (mm/tooth) | Surface roughness, $R_a (\mu m)$ | 3D surface roughness, $S_a (\mu m)$ | Vickers microhardness (HV) |
|----------|----------------------|----------------------|---------------------------------|------------------------------------|---------------------------|
| 1        | 80                   | 0.025                | $2.39 \pm 0.4$                  | $2.87 \pm 0.34$                    | 181.9                     |
| 2        | 80                   | 0.03                 | $2.82 \pm 0.3$                  | $3.38 \pm 0.23$                    | 188.8                     |
| 3        | 80                   | 0.035                | $2.94 \pm 0.2$                  | $3.53 \pm 0.25$                    | 192.36                    |
| 4        | 80                   | 0.04                 | $3.12 \pm 0.45$                 | $3.74 \pm 0.35$                    | 195.11                    |
| 5        | 100                  | 0.025                | $1.37 \pm 0.08$                 | $1.64 \pm 0.14$                    | 179.9                     |
| 6        | 100                  | 0.03                 | $2.14 \pm 0.13$                 | $2.57 \pm 0.23$                    | 187.23                    |
| 7        | 100                  | 0.035                | $2.51 \pm 0.15$                 | $3.01 \pm 0.37$                    | 196.32                    |
| 8        | 100                  | 0.04                 | $2.81 \pm 0.14$                 | $3.37 \pm 0.4$                     | 205.57                    |
| 9        | 120                  | 0.025                | $0.67 \pm 0.07$                 | $0.80 \pm 0.14$                    | 182.22                    |
| 10       | 120                  | 0.03                 | $0.69 \pm 0.07$                 | $0.83 \pm 0.15$                    | 189.47                    |
| 11       | 120                  | 0.035                | $1.03 \pm 0.1$                  | $1.24 \pm 0.2$                     | 199.89                    |
| 12       | 120                  | 0.04                 | $1.07 \pm 0.1$                  | $1.28 \pm 0.22$                    | 250.69                    |
| 13       | 140                  | 0.025                | $0.65 \pm 0.02$                 | $0.78 \pm 0.08$                    | 190.65                    |
| 14       | 140                  | 0.03                 | $0.67 \pm 0.03$                 | $0.80 \pm 0.09$                    | 200.69                    |
| 15       | 140                  | 0.035                | $0.87 \pm 0.04$                 | $1.04 \pm 0.1$                     | 245.57                    |
| 16       | 140                  | 0.04                 | $0.91 \pm 0.06$                 | $1.09 \pm 0.12$                    | 265.82                    |
particles from tool material are detached and stick to the end-milled sample creating rough surface. The results were similar with the findings of Biermann and Hollmann [45]. Furthermore, the time at which the tool meets the workpiece

Fig. 4 SEM images of end-milled surface of AISI 316L material machined at a $V_c = 80$ m/min and $f = 0.04$ mm/tooth, b $V_c = 140$ m/min and $f = 0.025$ mm/tooth

Fig. 5 2D Surface profile of machined surface at a $V_c = 80$ m/min, $f = 0.04$ mm/tooth, and b $V_c = 140$ m/min, and $f = 0.0025$ mm/tooth
The sample’s microhardness before end-milling was measured which was 257 HV along the surface. For each sample, three readings of microhardness were taken and the average of those was taken for analysis. It is shown in Table 3 that the superficial layers suffer thermal and plastic deformations on account of the heat generated in the primary zone during the end-milling process, thereby, affecting the mechanical features in the sample. The microhardness value of the selected cutting parameters was studied where the cutting speed was varied having constant feed rate and compared the results of hardness as shown in Table 3. The surface having a microhardness value of 265.82 HV at 20 μm beneath the surface. During end-milling, as the depth of cut was constant, severe shear deformations occurred which resulted in a considerably hardened layer on the milled surface. Furthermore, the microhardness index further decreased to 191 HV at a distance of 180 μm which remained unaltered after further decrement in the material inside. It is evident that the bulk material of specimen remains unaffected and there is no work-hardening that occurred on that region. Similar results were also presented by [48]. It is also evident that the affected area for the microhardness was 140 μm for all cutting conditions. The maximum value of microhardness was found to be 265.82 HV as compared with free sample. This increase in the value of microhardness improves the wear resistance of the machine’s surface for AISI 316L SS. The impact of cutting speed and feed rate on the microhardness of AISI 316L is presented in Fig. 8. It is clear that the hardness of the workpiece is greatly influenced by the end-milling which has a direct relationship with the cutting parameters. As the tool moves during the cutting process, plastic deformation occurs on the surface as well as underneath it. The deformation effects the material intrinsic properties [49]. As cutting speed raises, the plastic deformation also enhances that impacts the 316L properties resulting in change in flow stress properties.

3.3 Metallographic examination

Figures 9 and 10 show the SEM micrographs of samples immersed in Hank’s solution and HCL solution, respectively. Figures 9a–d show that the samples were not affected by the Hank’s solution. However, for 1 M HCl, the cracks were found on the surface of all four samples after 10 h of immersion. It is well known that chloride SCC is likely to occur when the concentration of the chloride ions is sufficient. It was found that these cracks were perpendicular to the point where the stress is directly applied. The cracks were in a parallel series propagating into the specimen. Growth of the fine cracks combined with each other resulted in bigger crack which damaged the whole part. The SCC phenomena was dependent on the crack density. The crack density was found to be higher for high surface roughness specimens. The crack density of the four samples having different surface roughness values immersed in HCL solution is presented in Table 4.

The highest crack density 60 mm/min was found that the sample has the highest surface roughness value of 2.82 ± 0.3 μm. The nature of the SCC in the samples was compared according to their difference in crack density ($\rho_c$) values (as shown in Fig. 10a–d). Figure 10a also shows that the presence of the cracks becomes shallow and long with increase of surface roughness. It was due to the irregularities found on the
surface of the test specimen. These irregularities in the feed marks and material flow affected the SCC density. For the sample with the $R_a = 1.07 \pm 0.1 \, \mu m$, the nature of the cracks was different. The value of the crack density was lower as $(\rho_c) = 48 \, \text{cracks/mm}^2$. It was due to the low $R_a$ value, which made the sample resist the crack propagation. The workpiece had smaller irregularities as compared with the sample with the $R_a = 2.82 \pm 0.3 \, \mu m$. The crack density was affected by the surface roughness of the specimens. When the $R_a$ increased, the value of the $\rho_c$ also increased (as shown in Fig. 10a–d).

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![Fig. 8](image) Microhardness variation with cutting speed and feed rate

![Fig. 9](image) Samples immersed in Hank’s solution after a 24 h, b 2 weeks, c 4 weeks, d 8 weeks

![Springer]
of the crack density was lower as \( \rho_c = 48 \text{ cracks/mm}^2 \). It was due to the low \( R_a \) value, which made the sample resist crack propagation. The workpiece had smaller irregularities as compared with the sample with the \( R_a = 2.82 \pm 0.3 \mu m \). The crack density was affected by the surface roughness of the specimens. When the \( R_a \) increased, the value of the \( \rho_c \) also increased.

Figure 11 indicates the surface roughness trend with crack density. During the milling process, it produces deformation layer which consists of an ultrafine layer that promotes oxidation while the inner layer is resistant to oxidation. This inner layer increases the susceptibility of the SCC towards the surface and the crack initiation [50]. The SCC was the result of two types of cracks, primary cracks, and secondary cracks. These cracks were produced longitudinally and showed a transgranular morphology. At surface roughness \( (R_a = 0.6 \mu m) \), the crack density is lower and the surface is resistant to produce pits and cracks while immersion in HCl solution for 8 h. There were no irregularities in either BUE or dislocation of the grain boundaries (Fig. 10a) that resist the initiation of deep and large number of cracks. However, in the highest surface of \( R_a = 2.8 \mu m \), the surface has BUE and large irregularities like holes and small cracks that were prone to the initiation of SCC as seen in Fig. 10d. The crack density is the highest and having deep cracks that totally damaged the specimen. These cracks were initiated after the end-milling from different surface defects: voids and a rough surface which resulted in pit formation. Those pits served as origin point for pitting of initial cracks. The ongoing cracks then propagated from the primary cracks in a perpendicular direction [51]. The results are in agreement with available results where it was reported that, with increased surface roughness value, stress concentration increases which ultimately promoted the SCC of [49].

| Sr # | Surface roughness, \( R_a \) (\( \mu m \)) | Type of environment | Time of immersion (h) | Crack density, \( \rho_c \) (cracks/mm\(^2\)) |
|------|------------------|------------------|------------------|------------------|
| 1    | 2.82             | 1 M HCl          | 10               | 60               |
| 2    | 1.07             | 1 M HCl          | 10               | 48               |
| 3    | 0.91             | 1 M HCl          | 10               | 46               |
| 4    | 0.65             | 1 M HCl          | 10               | 36               |
The surface roughness acted in direct proportion to the operating parameters viz., cutting speed (V_c) and feed rate (f), on the surface quality and hardness of the AISI 316L material surfaces produced during end-milling. The impression of surface roughness on the susceptibility of “stress corrosion cracking” for AISI 316L was also investigated. Concluding remarks are:

- The surface roughness acted in direct proportion to the V_c and behaved inversely to the f. An increase in the V_c tends to improve the surface quality but the trend was opposite for f which deteriorated the surface quality. The best results for the surface quality (minimum surface roughness) were observed for V_c = 140 m/min and f = 0.025 mm/tooth.
- The microhardness index enhance; thanks to increased V_c and f. The maximum value of microhardness noted was 265.82 HV which was achieved at 20 μm distance from the machined AISI 316L surface. It proved that the high microhardness is a pronounced variable against wear of the material which ultimately provides the corrosion cracking of the material.
- The machined samples with different surface roughness values (R_a) in Hank’s solution were reaction free while it was susceptible to the SCC in 1 M HCl solution.
- The impact of surface roughness on the SCC was studied in terms of crack density (σ_c). The increase in the R_a increased the value of the crack density, which meant that the AISI 316L SS sample with high R_a value was susceptible to the SCC more than the sample with the low R_a.

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**Data availability** All the data have been presented in the manuscript.

**Compliance with ethical standards**

**Conflict of interest** The authors declare that they have no conflict of interest.

**Code availability** Not applicable.

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**References**

1. Philip SD, Chandramohan P, Mohanraj M (2014) Optimization of surface roughness, cutting force and tool wear of nitrogen alloyed duplex stainless steel in a dry turning process using Taguchi method. Measurement 49:205–215. https://doi.org/10.1016/j.measurement.2013.11.037
2. Moharrami R, Sanayei M (2020) Improvement of indentation technique for measuring general biaxial residual stresses in austenitic steels. Precis Eng 64:220–227. https://doi.org/10.1016/j.precisioneng.2020.04.011
3. Bordjhi K, Jouzeau J-Y, Mainard D, Payan E, Delagoutte JP, Netter P (1996) Evaluation of the effect of three surface treatments on the biocompatibility of 316L stainless steel using human differentiated cells. Biomaterials 17:491–500. https://doi.org/10.1016/0142-9612(96)81723-2
4. Park JB (2012) Biomaterials science and engineering. Springer Science & Business Media doi: https://doi.org/10.1007/978-1-4613-2769-1
5. Ozcelik B, Kuram E, Simsek BT (2011) Comparison of dry and wet end milling of AISI 316 stainless steel. Mater Manuf Process 26: 1041–1049. https://doi.org/10.1080/10426914.2010.515645
6. Ajitanshu V, Shashi Kant C (2019) Optimizing machining process of E31 steel for improved surface roughness. Invertis Journal of Science and Technology 12:153–164. https://doi.org/10.5958/2454-762x.2019.00024.6
7. Nomani J, Pramanik A, Hilditch T, Littlefair G (2013) Machinability study of first generation duplex (2205), second generation duplex (2507) and austenite stainless steel during drilling process. Wear 304:20–28. https://doi.org/10.1016/j.wear.2013.04.008
8. Xavior MA, Adithan M (2009) Determining the influence of cutting fluids on tool wear and surface roughness during turning of
AISI 304 austenitic stainless steel. J Mater Process Technol 209: 900–909. https://doi.org/10.1016/j.matprotec.2008.02.068

9. Sultana AZ, Shariﬁ S, Kurniawan D (2015) Effect of machining parameters on tool wear and hole quality of AISI 316L stainless steel in conventional drilling. Procedia Manuf 2:202–207. https://doi.org/10.1016/j.promfg.2015.07.035

10. Zaman B, Sultana PN, Dhar NR (2020) Quantifying the effects of cooling condition, tool type and cutting parameters on machinability of turning AISI 4140 steel using full factorial DOE. J. Manuf. Syst.Sci 1(2):23–39 http://www.imperialopen.com/index.php/JPSMS/article/view/29

11. Rama Kotaiah K, Srinivas J, Babu KJ, Srinivas K (2010) Prediction of optimal cutting states during inward turning: an experimental approach. Mater Manuf Process 25:432–441. https://doi.org/10.1080/10426910903229321

12. Agarwal S, Rao PV (2008) Experimental investigation of surface/subsurface damage formation and material removal mechanisms in SiC grinding. Int J Mach Tools Manuf 48:698–710. https://doi.org/10.1016/j.ijmachtools.2007.10.013

13. Niinomi M (2019) Metals for biomedical devices. Woodhead publishing

14. Gresik W, Kruzsynski B, Ruszaj A (2010) Surface integrity of machined surfaces. Surf. Integr. Mach. Springer, In, pp 143–179. https://doi.org/10.1007/978-1-84882-874-2_5

15. Singh DK (2008) Manufacturing technology: theory and problems. Pearson Education India

16. Ben RA, Sidhom H, Braham C et al (2001) Effects of surface preparation on pitting resistance, residual stress, and stress corrosion cracking in austenitic stainless steels. J Mater Eng Perform 10: 507–514. https://doi.org/10.1007/s11599-001-0703-44638

17. Lin T-R (2002) Optimisation technique for face milling stainless steel with multiple performance characteristics. Int J Adv Manuf Technol 19:330–335. https://doi.org/10.1007/s001700200021

18. Asiltürk I, Akkus H (2011) Determining the effect of cutting parameters on surface roughness in hard turning using the Taguchi method. Measurement 44:1697–1704. https://doi.org/10.1016/j.measurement.2011.07.003

19. Tekner Z, Yeşılçay S (2004) Investigation of the cutting parameters depending on process sound during turning of AISI 304 austenitic stainless steel. Mater Des 25:507–513. https://doi.org/10.1016/j.matdes.2003.02.011

20. Ozcelik B, Bayramoglu M (2006) The statistical modeling of surface roughness during high-speed flat end milling. Int J Mach Tools Manuf 46:1395–1402. https://doi.org/10.1016/j.ijmachtools.2005.10.005

21. Danish M, Yahya S, Saha BB (2020) Modelling and optimization of thermophysical properties of aqueous titanium nanofluid using response surface methodology. J Therm Anal Calorim 139:3051–3063. https://doi.org/10.1007/s10973-019-08673-z

22. Aslanças K, Danish M, Hasçelik A, Mia M, Gupta M, Ginta T, Ijaz H (2020) Investigations on surface roughness and tool wear characteristics in micro-turning of Ti-6Al-4V alloy. Materials 13:2998–3018

23. Baek DK, Ko TJ, Kim HS (2001) Optimization of feedrate in a face milling operation using a surface roughness model. Int J Mach Tools Manuf 41:451–462

24. Stoică A, Kopăcă J, Cukor G (2005) Testing of machinability of mould steel 40CrMnMo7 using genetic algorithm. J Mater Process Technol 164:1624–1630. https://doi.org/10.1016/j.matdes.2006.01.011

25. Jasni NAH, Lajis MA, Kamdani K (2012) Tool wear performance of TiAlN/AlCrN multilayer coated carbide tool in machining of AISI D2 hardened steel. Adv. Mater. Res. Trans Tech Publ, In, pp 462–467. https://doi.org/10.4028/www.scientific.net/AMR.488-489.462

26. Chang L, Burke MG, Scenini F (2018) Stress corrosion crack initiation in machined type 316L austenitic stainless steel in simulated pressurized water reactor primary water. Corros Sci 138:54–65

27. Zhang W, Fang K, Hu Y et al (2016) Effect of machining-induced surface residual stress on initiation of stress corrosion cracking in 316 austenitic stainless steel. Corros Sci 108:173–184. https://doi.org/10.1016/j.corsci.2015.07.035

28. Hinds G, Wickström L, Mingard K, Tumbull A (2013) Impact of surface condition on sulphide stress corrosion cracking of 316L stainless steel. Corros Sci 71:43–52. https://doi.org/10.1016/j.corsci.2013.02.002

29. Balamurugan R, Balossier A, Rebele HS, Ferreira MF (2008) Corrosion aspects of metallic implants — an overview. Mater Corros 59:855–869. https://doi.org/10.1007/s00035-008-0417-3

30. Ibrahim MR, Sreedharan T, Hadi F et al (2017) The effect of cutting speed and feed rate on surface roughness and tool wear when machining machining D2 steel. Mater. Sci. Forum. Trans Tech Publ, In, pp 80–85. https://doi.org/10.4028/www.scientific.net/MSF.909.80

31. Mia M, Singh GR, Gupta MK, Sharma VS (2018) Influence of Ranque-Hilsch vortex tube and nitrogen gas assisted MQL in precision turning of Al 6061-T6. Precis Eng 53:289–299. https://doi.org/10.1016/j.precisioneng.2018.04.011

32. Gupta MK, Sood PK, Sharma VS (2016) Machining parameters optimization of titanium alloy using response surface methodology and particle swarm optimization under minimum-quantity lubrication environment. Mater Manuf Process 31:1671–1682. https://doi.org/10.1080/10426941.2015.1117632

33. Gupta MK, Sood PK, Sharma VS (2016) Optimization of machining parameters and cutting fluids during nano-fluid based minimum quantity lubrication turning of titanium alloy by using evolutionary techniques. J Clean Prod 135:1276–1288. https://doi.org/10.1016/j.jclepro.2016.06.184

34. Thiele JD, Melkote SN, Peascoe RA, Watkins TR (2000) Effect of cutting-edge geometry and workpiece hardness on surface residual stresses in finish hard turning of AISI 52100 steel. J Manuf Sci Eng 122:642–649. https://doi.org/10.1115/1.1286369

35. Hua J, Shivpuri R, Cheng X, Bedekar V, Matsumoto Y, Hashimoto F, Watkins TR (2005) Effect of feed rate, workpiece hardness and cutting edge on subsurface residual stress in the hard turning of bearing steel using chamfer+ hone cutting edge geometry. Mater Sci Eng A 394:238–248. https://doi.org/10.1016/j.msea.2004.11.011

36. Nurhaniza M, Arifin M, Mustapha F, Baharudin B (2016) Analyzing the effect of machining parameters setting to the surface roughness during end milling of CFRP-aluminium composite laminates. Int J Manuf Eng 2016: https://doi.org/10.1155/2016/4680380

37. Mia M, Gupta MK, Singh G et al (2018) An approach to cleaner production for machining hardened steel using different cooling-lubrication conditions. J Clean Prod 187:1–10. https://doi.org/10.1016/j.jclepro.2018.03.279

38. Zahoor S, Saleem MQ, Abdul-Kader W (2019) Improving surface integrity aspects of AISI 316L in the context of bioimplant applications. Int J Adv Manuf Technol 105:2857–2867. https://doi.org/10.1007/s00170-019-04444-0

39. Cui X, Zhao J, Jia C, Zhou Y (2012) Surface roughness and chip formation in high-speed face milling AISI H13 steel. Int J Adv Manuf Technol 61:1–13. https://doi.org/10.1007/s00170-011-3684-9
42. Yasir TL, Ginta B, Ariwahjoedi AUA, Danish M (2016) Effect of cutting speed and feed rate on surface roughness of AISI 316l SS using end-milling. ARPN J Eng and App Sci 11:2496–2500
43. Zhang JZ, Chen JC, Kirby ED (2007) Surface roughness optimization in an end-milling operation using the Taguchi design method. J Mater Process Technol 184:233–239. https://doi.org/10.1016/j.jmatprotec.2006.11.029
44. Yasir M, Ginta TL, Alkali AU, Danish M (2015) Experimental investigation to improve surface integrity of biomedical devices by end-milling AISI 316L stainless steel. Appl Mech Mater 789-790:141–145. https://doi.org/10.4028/www.scientific.net/AMM.789-790.141
45. Biermann D, Hollmann F (2017) Thermal effects in complex machining processes: final report of the DFG Priority Programme 1480. Springer. https://doi.org/10.1007/978-3-319-57120-1
46. Danish M, Ginta TL, Habib K, Carou D, Rani AMA, Saha BB (2017) Thermal analysis during turning of AZ31 magnesium alloy under dry and cryogenic conditions. Int J Adv Manuf Technol 91: 2855–2868. https://doi.org/10.1007/s00170-016-9893-5
47. Danish M, Ginta TL, Habib K, Abdul Rani AM, Saha BB (2019) Effect of cryogenic cooling on the heat transfer during turning of AZ31C magnesium alloy. Heat Transf Eng 40:1023–1032. https://doi.org/10.1080/01457632.2018.1450345
48. Arunachalam RM, Mannan MA, Spowage AC (2004) Residual stress and surface roughness when facing age hardened Inconel 718 with CBN and ceramic cutting tools. Int J Mach Tools Manuf 44:879–887. https://doi.org/10.1016/j.ijmachtools.2004.02.016
49. Zurita Hurtado OJ, DiGraci Tiralongo VC, Capace Aguirre MC (2017) Effect of surface hardness and roughness produced by turning on the torsion mechanical properties of annealed AISI 1020 steel. Rev Fac Ing Univ Antioquia 55–59. https://doi.org/10.17533/udea.redin.n84a07
50. Chang L, Burke MG, Scenini F (2019) Understanding the effect of surface finish on stress corrosion crack initiation in warm-forged stainless steel 304L in high-temperature water. Scr Mater 164:1–5. https://doi.org/10.1016/j.scriptamat.2019.01.032
51. Arola D, Williams CL (2002) Estimating the fatigue stress concentration factor of machined surfaces. Int J Fatigue 24:923–930. https://doi.org/10.1016/S0142-1123(02)00012-9

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