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Research Article

The Effect of Feed and Depth of Cut Parameters on Surface Roughness and Chip Morphology in X2CrNiMoN2253 Duplex Stainless Steel Materials

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ABSTRACT

Machining is one of the primary methods used to produce precision machine parts. Machining operations are influenced by many parameters. The most important of these parameters are feed and depth of cut. In addition, as a function of these parameters, many technical characteristics, particularly surface roughness, of the parts produced by machining change. For this reason, it is very important to monitor the machining parameters of the workpieces to be machined and to change them if necessary. Workpieces from many different groups of materials can be machined, but it is more important to monitor and control the machining parameters in stainless steels, which are classified as difficult-to-machine materials. In this study, the optimum machining conditions were investigated to obtain the lowest surface roughness values on stainless steel materials (X2CrNiMoN2253). The experiments were started with two different depths of cut (0.8 mm -1 mm) and three different feeds (0.1 mm/rev - 0.15 mm/rev and 0.2 mm/rev). It is understood that the feed is highly foremost on the surface roughness and changes the experimental results up to three times, however, the effect of cutting depth was limited. In the experiments, the best experimental results were obtained under 0.1 mm/rev feed. For a detailed analysis of the effect of the depths of cut values on the surface roughness, three additional depths of cut values (1.25 mm-1.5 mm-1.75 mm) were used under 0.1 mm/rev feed. In these additional experiments, it was observed that the effect of cutting depth was still limited, and the surface quality deteriorated with increasing cutting depth.

1. INTRODUCTION

Machining has significant superiority compared to numerous other manufacturing processes. These superior characteristics are directly affected by machining (cutting) circumstances involving cutting speed, feed, and depth of cut [1]. Machining is used to machine miscellaneous materials to meet the specific requirements of many industrial sectors, particularly the automotive and aerospace industries. However, some materials, such as stainless steel, are more challenging to machine as compared to other materials. The primary reasons for this difficulty are the weak thermal conductivity and the strong strain-hardening tendency of stainless-steel materials. Determining the appropriate cutting conditions is critical to machining these difficult-to-machine materials [2, 3].

The difficulties encountered in machining stainless steel have attracted the attention of many researchers. Three different cutting parameters (depths of cut, cutting speeds, and feeds) were used by Subbaiah et al. [4] to machine AISI 4340 steel material. In their investigation, feed was the dominant influence on surface roughness, affecting Ra by 68.5% and Rz by 31.2%. They found that tool wear increased as material hardness and cutting speed increased. According to Santhanakumar et al. [5], the surface roughness values improved as the cutting speed rose and deteriorated as the feed increased. The investigators also stated that a raise in the cutting speed accelerated the wear of the tool and that with intensified tool wear, the surface roughness deteriorated. Rashid et al. [6] found that 99.16% of the surface finish depended on the feed values and that tool wear increased at lower feed values. The tool wear investigation on ferritic stainless steel (AISI 430) was performed by Pekşen and Kalyon [7]. The analysis involved three different feeds and cutting speeds. After analyzing the results, the investigators concluded that feed and cutting speed dramatically affect tool life. The investigators also monitored the types of wear (notch, crater, and flank) on the cutting tool. Ebrahimi et al. [8] performed machining experiments on AISI 360 (17-4 PH) martensitic stainless steel. The investigators studied both surface roughness and tool wear values during the machining operation. It was noted that both feed and cutting speed have a foremost impact on tool wear. The researchers also found that with properly selected parameters, the surface roughness values decreased by 23%.

Del Risco-Alfonso et al. [9] studied austenitic stainless steel (AISI 316L) at three cutting speeds and concluded that cutting speed had a direct influence on tool life. The main influence on tool wear was dependent on cutting speed although feed endured a negative outcome on tool wear. The machinability of austenitic stainless steel materials (AISI 304) using various cutting speeds, feeds, and depths of cut (under dry conditions) was investigated by Chen et al. [10]. The tool used in their investigation showed significant wear at the beginning, the wear increased at a later stage, and then severe tool wear was detected on the cutting tool. The investigators noticed that this wear caused the surface roughness values to deteriorate from 1.4 µm to 19.4 µm. Similarly, He et al. [11] showed that the rate of increase in tool wear changes step by step. In the first stage, rapid tool wear was observed, then it increased gradually, and finally, it increased rapidly. Surface roughness and tool wear experiments on AISI 316 stainless steel (austenitic) were performed by Derani et al. [12]. The investigators studied both nose and flank wear. Their investigation showed that although tool wear increased, the surface roughness was nearly constant. Szczotkarz et al. [13] studied tool wear on stainless steel (AISI 316) material underneath different machining conditions. The researchers point out that improper cutting conditions can lead to accelerated tool wear. In their study, Asiltürk et al. [14] analyzed the feed and depth of cut parameters on AISI 4140 material. They found that feed was the most dominant factor (87.7%) related to surface roughness. They emphasized that the depth of cut has a significant effect (28.6%) on tool vibration. Demirpolat et al [15] in their study analyzed the cutting speed, feed and depth of cut parameters on AISI 52100 material. The researchers emphasized that the surface roughness deteriorated as the feed and depth of cut values increased. The researchers also found that the chip shapes were significantly affected by the feed values.

In conducting the literature review, it was comprehended that there are countless investigations on stainless steel. However, only a limited amount of research has been found in the literature on X2CrNiMoN2253. In the current study, the reaction of different feed and depth of cut parameters on X2CrNiMoN2253 duplex stainless-steel material, which belongs to the group of difficult-to-machine materials, was investigated. For this purpose, the change in tool wear and surface roughness was investigated.

2. MATERIALS AND METHOD

A duplex stainless-steel material X2CrNiMoN2253 was employed in the machining investigations. Table 1 displays the chemical composition of this investigated material.

TABLE I
The chemical composition of X2CrNiMoN2253 materials

Element	Cr	Ni	Mo	Mn	C
wt.%	22.69	4.84	3.11	1.40	0.015

Machining operations were performed on a CNC turning center (Goodway GLS1500M) under dry machining conditions (without coolant) using a TNMG160404-HA insert (Korloy) and a PTGNR2020K16 tool holder (Seco). In the experiments, the cutting speed (V) was preferred as 180 m/min. Two different depth of cut values (0.8 mm and 1.00 mm) and three different feeds (0.10 mm/rev, 0.15 mm/rev, and 0.20 mm/rev) were used in the experiments (Table 2). The formula specified in Equation 1 was used to calculate the machining time [1].

$$T = \frac{\pi \times d \times l}{f \times 1000 \times V} \quad (1)$$

Where: T is the machining time, d is the workpiece diameter, l is the cutting length, f is the feed, V is the cutting speed.

TABLE II
The machining parameters

Depth of cut a_p (mm)	*Feed* f (mm/dev)	Machined diameter (mm)	Machining length (mm)	Machining time (min)
0.80	0.10	47.0	25	0.2051
0.80	0.15	45.4	25	0.1321
0.80	0.20	43.8	25	0.0956
1.00	0.10	41.8	25	0.1824
1.00	0.15	39.8	25	0.1158
1.00	0.20	37.8	25	0.0825

The workpieces were machined in nine passes, starting from Ø47 mm and going down to Ø28.8 mm. In each pass, the machining operation was conducted with a 25 mm longitudinal cutting length (Table 2). Although the cutting tool removes chips with a cutting length of 25 mm each time, the machining time has changed due to the change in the workpiece diameter value. The machining time, which was 0.2051 minutes in the first pass, was calculated as 0.0825 minutes in the last pass. Thus, the cutting tool performed a total of 0.8135 minutes of machining.

All machining operations were carried out under dry machining conditions by mounting the workpiece in the chuck between the tailstocks. The surface roughness results were recorded after each turning pass. The surface roughness average (Ra), surface roughness maximum average (Rz), and surface roughness maximum (Rt) values were utilized for the surface roughness measurements.

The arithmetic mean of the measurements taken five times at equal angular intervals (72°) around the workpiece was used to calculate each surface roughness parameter. A measuring terminal (Mahr M300) and a measuring device (Mahr Marsurf RD18) were employed for the measurements. In addition, all measurements were taken on the CNC turning center without the need to remove the workpieces from the chuck thanks to the Bluetooth connection. The measurements are explained in Figure 1.

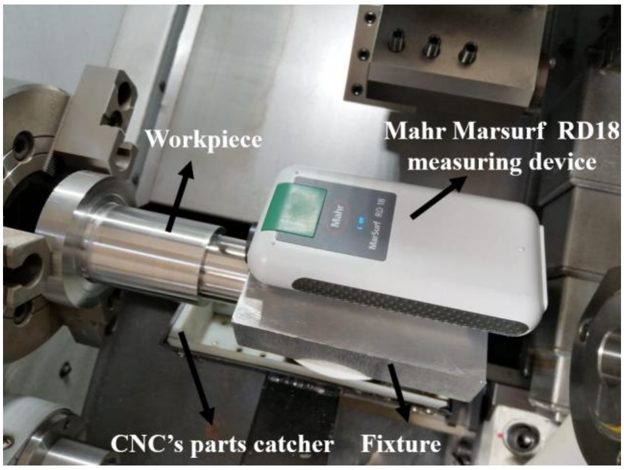

Figure 1. The Surface roughness measurement

Tool wear measurements were performed after all machining operations were completed. A toolmaker's microscope (Mahr MM200) combined with a camera (M-shot MD30) was utilized for this purpose. The tool wear measurements performed with the toolmaker's microscope are pointed in Figure 2.

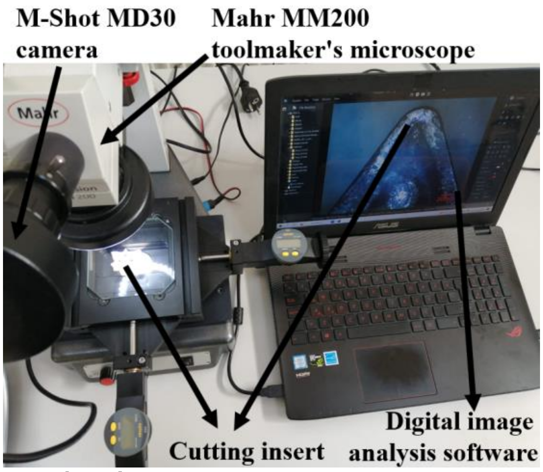

Figure 2. The tool wear measurements

3. RESULT AND DISCUSSION

3.1. Surface Roughness

After each machining operation on the CNC turning center, the surface roughness values were recorded without removing the workpiece from the CNC turning center using a surface roughness measuring device with a Bluetooth connection. The surface roughness values Ra, Rz, and Rt derived from the measurements are indicated in Table 3.

TABLE III
The machining parameters

Depth of cut a_p (mm)	*Feed* f (mm/rev)	Ra (μm)	Rz (μm)	Rt (μm)
0.8	0.1	1.528	7.142	8.628
0.8	0.15	2.471	10.35	11.64
0.8	0.2	4.147	16.47	17.09
1.0	0.1	1.414	8.552	11.50
1.0	0.15	2.801	13.60	16.87
1.0	0.2	4.693	17.59	18.20

In order to better understand the three surface roughness values (Ra, Rz, and Rt) depicted in Table 3, the impact of the feed and depth of cut on the surface roughness of the workpiece was analyzed. The figure created by using data including depth of cut and feed values from experimental data is depicted in Figure 3.

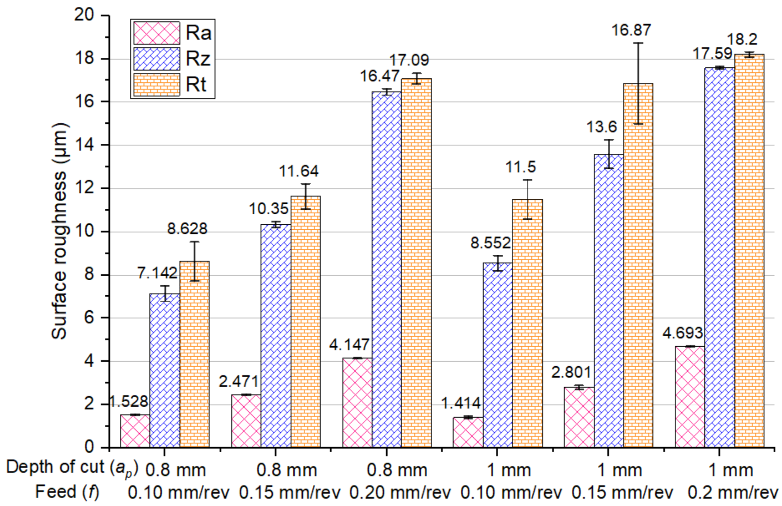

Figure 3. The surface roughness measurements depend on depth of cut and feed values.

Numerous cutting parameters directly affect machining operations. Each of these parameters has a different effect on the workpiece's features. Many studies have emphasized that the most noticeable impact on workpiece surface roughness values depends on the feed [6-7]. In this study, in parallel with the literature, it is clearly seen that the most impactful parameter in terms of average surface roughness is the feed value. It is clear that increasing the feed for both depths of cut (0.8 mm and 1.0 mm) causes serious deterioration in the surface quality (Figure 3). In the trials, the best surface roughness values were acquired at the lowest feed (0.10 mm/rev). In the experiments with a 0.8 mm depth of cut, when the feed was increased, it was determined that the surface roughness deterioration was 1.58 times and then 1.68 times, respectively. Similarly, in the experiments performed with a depth of cut (1.0 mm), depending on the increase in the feed, first 1.98 times distortion and then 1.68 times deterioration were observed. Figure 3 also shows the deviation observed in the surface roughness measurements. During the experiments, the chip control problem occurred in the experiments with ap=1 and f=0.15. Therefore, a significant deviation was observed in this experiment compared to other machining experiments.

The ANOVA analysis was implemented to investigate the effect of the depth of cut (0.8 mm and 1 mm) and the feed (0.1 mm/rev, 0.15 mm/rev, and 0.2 mm/rev), which are the experimental parameters, on the surface roughness of the workpiece. The ANOVA analysis of the surface roughness values are shown in Table 4 for Ra, Table 5 for Rz, and Table 6 for Rt.

TABLE IV
ANOVA analysis of surface roughness values (Ra)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Depth of cut a_p (mm)	1	0.09703	0.09703	1.71	0.321
Feed f (mm/rev)	2	8.82525	4.41263	77.86	0.013
Error	2	0.11335	0.05667		
Total	5	9.03563			

TABLE V

ANOVA analysis of surface roughness values (Rz)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Depth of cut a_p (mm)	1	5.568	5.5681	8.35	0.102
Feed f (mm/rev)	2	84.614	42.3070	63.41	0.016
Error	2	1.334	0.6672		
Total	5	91.516			

TABLE VI

ANOVA analysis of surface roughness values (Rt)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Depth of cut a_p (mm)	1	14.143	14.143	6.62	0.124
Feed f (mm/rev)	2	57.685	28.843	13.50	0.069
Error	2	4.273	2.137		
Total	5	76.102			

The ANOVA analysis (Tables IV, V, and VI) examined the weightiness of both process parameters on the workpiece surface roughness. The efficiencies of the cutting parameters were calculated according to the Adj SS values of the parameters and are shown in Figure 4 for Ra, Figure 5 for Rz, and Figure 6 for Rt.

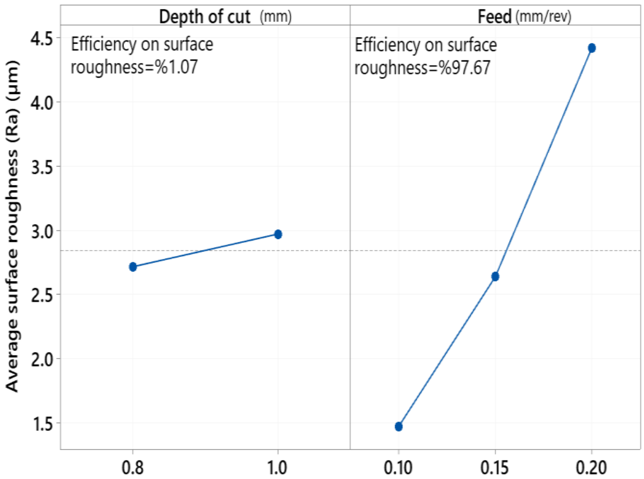

Figure 4. The effect of parameters on surface roughness (Ra)

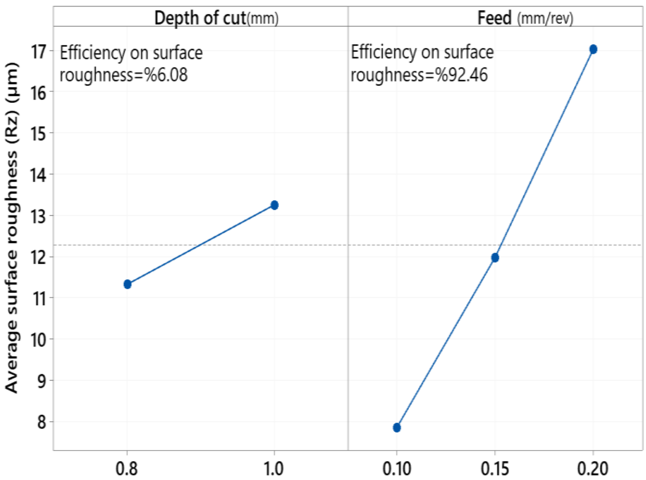

Figure 5. The effect of parameters on surface roughness (Rz)

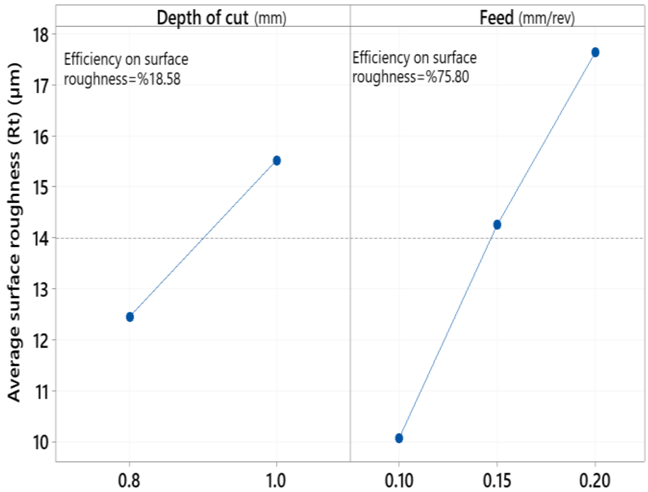

Figure 6. The effect of parameters on surface roughness (Rt)

As can be clearly seen in Table 4, the feed parameter is quite significant in this data set, as the p-value of the feed parameter is less than 0.05. In the R-sq analysis, the R-sq(adj) value was calculated as 98.75% and the R-sq(adj) value was calculated as 96.86%. Figure 4 clearly shows the obvious effect of feed (97.67%) on the machined part surface roughness. It is well known that the feed parameter has an obvious effect on the surface roughness [14-16].

It is interesting to note that despite the obvious effect of feed on surface roughness, the effect of depth of cut is very limited (1%). Although feed is the most dominant parameter in the ANOVA analysis conducted for the Rz and Rt values, it is interesting to note that the effect of the depth of cut is 6% for Rz and 18% for Rt. In this case, it can be argued that it is important to perform ANOVA analysis within different surface roughness parameters. The effect of the other process parameter, the depth of cut parameter, on the surface roughness should also be analyzed. To further investigate the effect of depth of cut on surface roughness, three additional depths of cut (1.25 mm-1.5 mm-1.75 mm) were used at a feed of 0.1 mm/rev. In addition to the existing two experiments conducted at a feed of 0.1 mm/rev, the results of three additional experiments at different depths of cut are shown in Table 5. With these experiments, the cutting tool, which was previously used for 0.8135 minutes, was used for a total of 1.2341 minutes.

TABLE V

The existing and new experiments

Depth of cut a_p (mm)	*Feed* f (mm/rev)	Ra (µm)	Rz (µm)	Rt (µm)	Experiments info
0.80	0.10	1.528	7.142	8.628	Existing
1.00	0.10	1.414	8.552	11.50	Existing
1.25	0.10	1.435	8.495	11.98	New
1.50	0.10	1.889	10.60	15.10	New
1.75	0.10	1.757	10.69	12.84	New

The values from Table 5, obtained for a total of five different cutting depths, are shown in Figure 5.

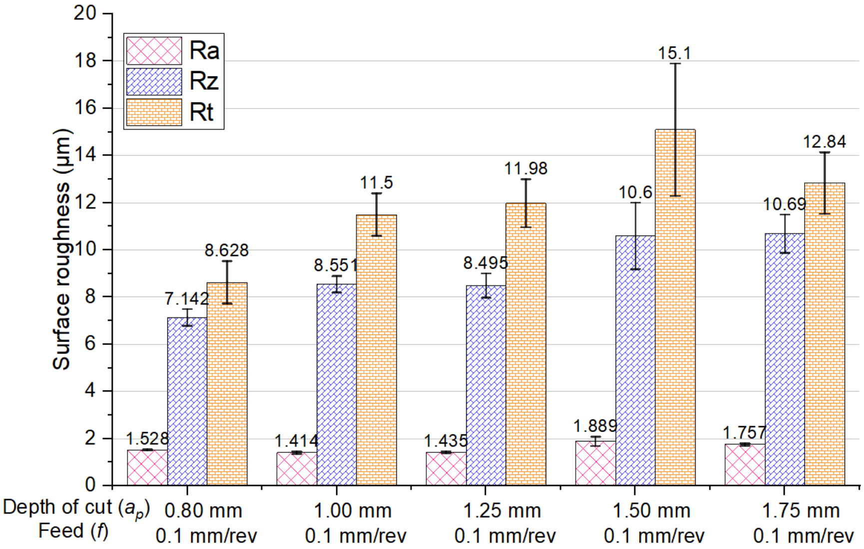

Figure 5. The surface roughness measurements depends on depth of cut values

As depth of cut becomes deeper, the surface roughness of the workpiece deteriorates. However, in the experiments with a 1.5 mm depth of cut, the surface roughness deterioration was greater than expected. In this experiment, large deviations are observed in the surface roughness obtained in this experiment.

Although surface roughness is affected by many factors, the most dominant effect is generally due to feed. The following equation (Equation 2) is commonly used to calculate theoretical surface roughness values [1].

$$R_{th} = \frac{f^2}{8 \times r_\varepsilon} \quad (2)$$

Where: R_{th} is the theoretical surface roughness values, r_ε is the nose radius of the cutting tool radius.

As can be seen from Equation 2, the feed and the nose radius value of the cutting tool are critical in calculating the theoretical surface roughness. The nose radius value of the cutting tool was held constant in the experiments, therefore the theoretical surface roughness changes only as a function of feed. Since increasing the depth of cut values increases the cutting forces [15], vibrations [14] the deflection of the cutting tool increases, and the surface roughness deteriorates. In addition, the cutting mechanics change due to the increased chip cross-section, and the surface roughness deteriorates [2].

3.2. Tool wear

The duplex stainless steel workpiece (X2CrNiMoN2253) was machined in a total of nine passes., with six initial experiments and three additional experiments. The cutting tool was utilized for a total of 1.2341 minutes during these studies, compared to its previous usage of 0.8135 minutes. After these operations, the cutting tool was inspected for tool wear (Figure 6). The images of the top surface of the cutting tool (Figure 6b), the flank surface (Figure 6c), the nose surface (Figure 6d), and the top surface at an angle of 10° (Figure 6e) were examined. Tool wear inspections were performed using the measurement procedures specified in ISO 3685:1993 (Tool-life testing with single-point turning tools) were used [16].

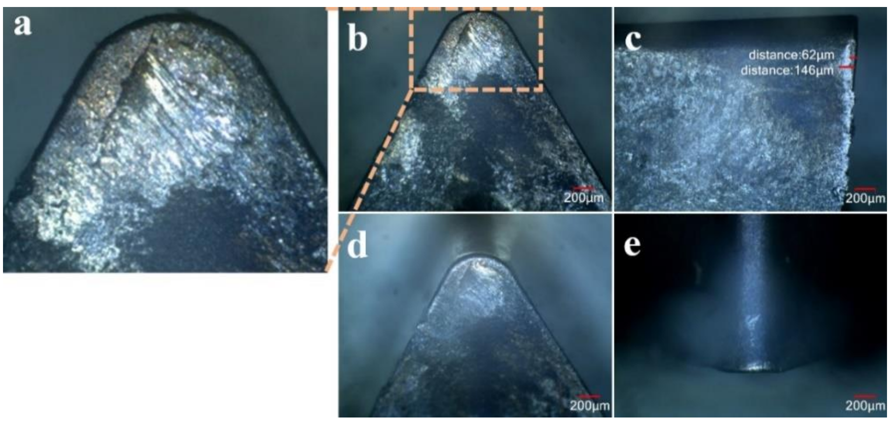

Figure 6. The tool wear inspection

It is a well-established fact that cutting tool wear increases over time. Since the total cutting time of the cutting tool is very short, the amount of wear was also less. A maximum of 146 µm of flank wear was recorded (Figure 6c). In addition, no significant notch wear was observed. The top surface of the tool (Figure 6b) was examined in detail (Figure 6a). It is evident that the coating on the top surface of the cutting tool was severely worn, and crater wear had begun. It is also clear that the nose wear is quite low. Although the cutting speed in the experiments was slightly higher than the tool manufacturer's recommendation, tool wear was limited due to the short cutting time.

3.2. Chip Morphology

It is well known that chips with long morphologies should be avoided in machining processes. Since chip evacuation is crucial in industrial applications, it is important to choose machining conditions that aim to produce short chips. For this reason, it is necessary to select the optimum experimental conditions both scientifically and industrially. The chips obtained as a result of the machining process are directly related to the cutting parameters. Different chip morphologies were obtained depending on the cutting depth and feed used in the experiments (Figure 7).

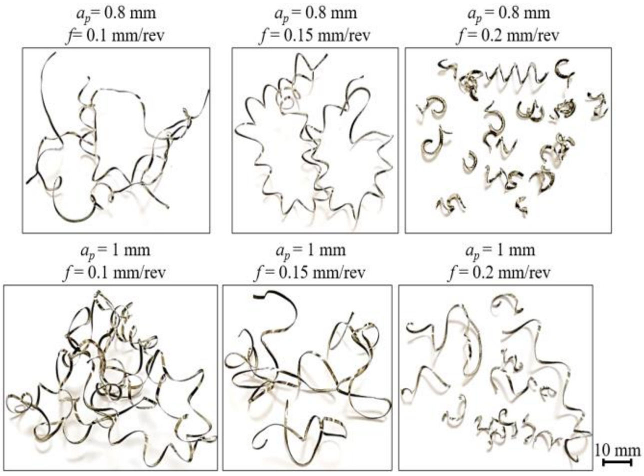

Figure 7. The chip morphologies depends on depth of cut and feed values.

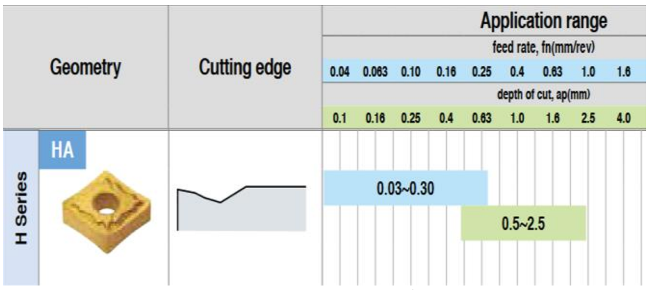

Figure 8. HA Chip breaker form [15]

Chip morphology stands a function of multiple cutting parameters. Depth of cut, feed, and cutting speed are the most important. However, cutting tools often have special chip breaker forms designed for specific machining conditions (Figure 8). The values recommended by the tool manufacturer are used to fulfill the functions of these chip breaker forms. The depth of cut and feed values used in the experiments also have a significant effect on chip morphology (Figure 7). Moreover, Figure 7 clearly shows that increasing the feed shortens the chip lengths. It is also clear that the raise in the value of the depth of cut shortens the chip lengths, although not as much as the feed.

It is known that chip breaking becomes difficult when applications require elevated cutting speeds, low feed, and depths of cut. In these experiments, this situation occurred generally, and the chip breaker shape was not effective in general, except for 0.2 mm/rev feed. The chip shapes were examined in Figure 9 by keeping the feed constant and depending only on the depth of cut.

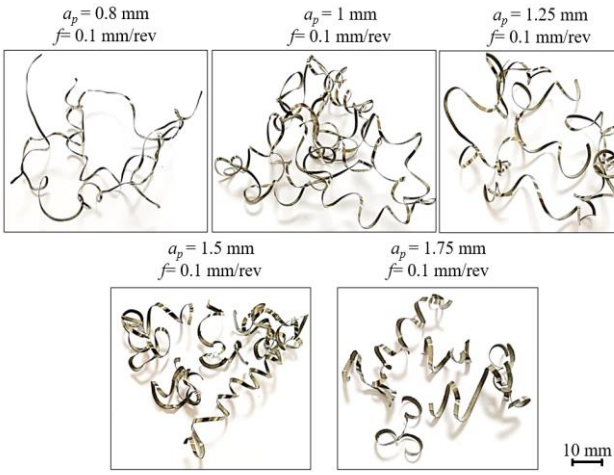

Figure 9. The chip morphologies depends on depth of cut

Figure 9 confirms that the chip shapes are affected by the depth of cut. However, this effect is not obvious. Relatively short chips were obtained at only 1.5 mm and 1.75 mm.

The cross-sectional area of the chips varies as a function of the approach angle, feed, and depth of cut values. Since the approach angle and feed were constant under the experimental conditions shown in Figure 9, only the cross-sectional area of the chips changed depending on the feed value. In Figure 9, it can be clearly seen that the chip cross-section has widened, but the long chip morphologies do not change in the experiments. It is well known that the feed effects the chip morphologies [15] and must be increased to obtain short chips in cutting tools. In this case, it can be proposed that there is no change in chip length due to the low feed value.

In this case, it is clear that a high feed (0.2 mm/rev) should be used to obtain the most appropriate chip shapes according to the current experimental parameters. The fact that the chip breaker shape is not active is a situation that should be avoided, as it makes chip control difficult and affects the surface roughness.

4. CONCLUSION

In the current study, the most favorable machining conditions were investigated to obtain the lowest surface roughness values on stainless steel materials (X2CrNiMoN2253) using different cutting depth of cuts values (0.8 mm -1 mm) and feed values (0.1 mm/rev - 0.15 mm/rev and 0.20 mm/rev). The following conclusions were obtained as a result of this study.

The feed and the depth of cut values have a distinct change on the surface roughness (Ra). However, it is comprehended that the feed has a rather dominant effect (97.67%) on the surface roughness values. Compared to Ra values, it is understood that the effect of feed on other surface roughness parameters (Rz, Rt) decreases.

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It has been determined that the depth of cut has a certain effect on the surface roughness. In general, the surface roughness deteriorates as the depth of cut becomes deeper. Unlike Ra values the effect of the depth of cut parameter has become evident in Rz and Rt values. The effect of the cutting depth was calculated as 1.07% for Ra, 6.08% for Rz and 18.58% for Rt.

The tool wear value is also very limited since the total cutting time of the cutting tool is very short. In the examinations, the utmost value of the flank wear was determined as 146 µm.

In terms of chip morphology, it has been observed that the chip morphology changes significantly depending on the feed. It was found that a high feed and a high depth of cut values contribute to the formation of better chip forms. Chip control could not be partially achieved at low feeds.

In present study, the effectiveness of feed and depth of cut on the workpiece surface roughness and cutting tool wear was investigated. In future studies, the effects of different cutting parameters on cutting forces and cutting tool vibrations can be investigated. Also, different coolant and MQL cutting conditions can be investigated.

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