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The Effect of Machining Conditions on Surface Roughness and Burr Formation in Milling of AISI 304 Cast Stainless Steel

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Keywords: AISI 304 stainless steel, Face milling, Burr height, Surface roughness, Mist cold air cooling

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ABSTRACT

AISI 304 quality stainless steels are a very common type of stainless steel because they have high mechanical properties and high corrosion resistance. Stainless parts with complex and large dimensions are produced by the casting method. The machinability of stainless steels produced by casting is even more difficult than forging methods. In this study, the effects of three different cutting speeds, feed rates and constant cutting depth on the surface roughness and burr formation in dry and mist cold air (MCA) conditions were investigated in milling of AISI 304 stainless cast steel. As a result, an improvement between 15% and 48% was achieved in the average surface roughness (Ra) obtained in machining with MCA compared to dry machining conditions. In both cutting conditions, the increasing feed rate increased the burr height, while the increase in cutting speed decreased the burr height. MCA application provided an average of 9% reduction in burr height

AISI 304 Paslanmaz Döküm Çeliğinin Frezelemesinde İşleme Şartlarının Yüzey Pürüzlülüğü ve Çapak Oluşumuna Etkisi

ÖZ

AISI 304 kalite paslanmaz çelikler yüksek mekanik özelliklere ve yüksek korozyon direncine sahip olduklarından oldukça yaygın kullanılan bir paslanmaz çelik çeşididir. Karmaşık ve büyük ebatlara sahip paslanmaz parçalar döküm yöntemi ile üretilmektedir. Döküm ile üretilen paslanmaz çeliklerin işlenebilirliği dövme yöntemlerine göre daha da zor olmaktadır. Bu çalışmada, AISI 304 paslanmaz döküm çeliğinin frezelenmesinde kuru ve buharlı soğuk hava şartlarında üç farklı kesme hızı, üç farklı ilerleme miktarı ve sabit kesme derinliğinin yüzey pürüzlülüğü ve çapak oluşumuna etkisi araştırılmıştır. Sonuç olarak buharlı soğuk hava (BSH) ile işlemede elde edilen yüzey pürüzlülüklerinde kuru işleme şartlarına göre %15-%48 arasında bir iyileşme sağlanmıştır. Her iki kesme şartında, ilerleme miktarı çapak yüksekliğini artırırken kesme hızının artışı çapak yüksekliğini azaltmıştır. BSH uygulaması çapak yüksekliğinin ortalama %9 azalmasını sağlamıştır.

Anahtar Kelimeler: AISI 304 paslanmaz çelik, Yüzey frezeleme, Çapak yüksekliği, Yüzey pürüzlülüğü, Buharlı soğuk hava soğutma

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1. Introduction

Austenitic stainless steels are characterized as the richest stainless-steel group due to their use and the high alloy qualities they have. Austenitic stainless steels are non-magnetic, normalizing and hardening cannot be done to these steels at room and high temperatures as they retain their austenitic internal structure bearing a face-centered cubic lattice. Ductility, toughness, and formability are very good at low-temperature values in the annealed state. Their strength can only be increased by cold forming. Austenitic stainless steels contain 16%-26% Cr, up to 35% Ni and up to 20% Mn alloy elements. Ni and Mn undertake the basic austenite formation. Among the austenitic stainless-steel grades, AISI 301 and AISI 304 are the steel types that contain the least alloying elements. AISI 304 quality stainless steel is the most widely used type of stainless steel with its excellent machinability, good ductility and corrosion resistance [1-2].

Milling is a well-known machining technique in the metalworking industry. The surface quality of components determines their quality. Excessive heat, tool wear, and poor surface quality can all be caused by high friction between tool contacts. The use of cooling lubricants in machining is critical for improving machining performance. However, the usage of cooling lubricants is expensive, pollutes the environment, and endangers operator health [3-4]. Surface roughness is the most important indicator of machined item surface quality and one of the most stringent client requirements. Noordin and his team It has been established that the feed rate influences surface roughness, and that using a lower feed rate leads in greater surface quality. It was also revealed that when cutting speed increased, the resulting surface roughness value increases [5]. Austenitic stainless steels' enhanced ductility explains higher surface roughness values at higher cutting speeds. This increases the possibility of separate and unstable markers emerging (BUEs). Surface quality suffers due to the presence of large and unstable BUE [6]. There is much research in the literature on reducing tool wear and BUE formation, improving surface roughness, and using alternative cooling and lubrication methods instead of cooling lubricants when machining stainless steel materials [7].

Rahman et al. [8] found that high-pressure cooling reduces cutting resistance and improves surface quality on milling machines. Liew provided better surface quality with fog cooling than traditional cooling methods when milling AISI 420 alloy using coated and uncoated carbide end mills [9]. Braham Bouchnaketal investigated tool wear when machining duplex stainless steel by cooling with high-pressure water. Compared to dry cutting, a better surface is achieved when processed by cooling with pressurized water. Pressure cooling extended the service life by 20% [10]. Chockalingam and Wee studied the effects of synthetic oils, aqueous emulsions and compressed cold air on cutting resistance, surface roughness and tool wear when milling stainless steel AISI 304. Aqueous emulsion processing has achieved better surface quality and lower cutting power. While traditional cooling lubricants require a high feed rate to reduce surface roughness, a low feed rate is suitable for cold compressed air [11]. Şirin and Şirin investigated the effects of cooling conditions (MQL, LN2 and MQL+LN2) on surface roughness, cutting temperature and flank wear in milling AISI 316L stainless steel. Milling with the MQL+LN2 cooling method significantly improved machining output compared to other cooling conditions [12].

Yıldırım investigated the effects of nano-graphite reinforced cutting fluid, oil flow, and pressure on Ra and temperature on cutting zone in AISI 316 steel milling at different rates, and nanofluid gave better results for eco-friendly machining [13]. Kuram investigated the effect of different coated cutting tool performance on tool wear, cutting pressures, and surface roughness while milling AISI 304 stainless steel material and AlTiN coated inserts showed the worst performance [14]. Altınkaya and Güllü achieved the best cutting tool performance with TiAlN coated tools in AISI 316 stainless steel machining with insert end mills [15]. Çakıroğlu and Uzun stated that in high feed milling of vermicular graphite cast iron, the resultant force decreases as the hardness of the material decreases, and the surface roughness worsens as the feed rate increases [16].

In milling operations, burrs may occur at the entrance and exit of the cutting tool to the workpiece. Generally, burr formation is defined as plastically deformed materials formed at the corners and edges of the part due to plastic flow from cutting operations. These unwanted materials can often occur in different shapes and forms, depending on the machining process and workpiece materials [17, 18]. Burr formation causes secondary machining operations known as deburring operations, increasing the cost of machining parts. In addition, while causing dimensional errors, it can negatively affect the quality of the part, while it can cause safety problems that can lead to injuries to workers during processing [17,19]. Therefore, it is necessary to control and minimize the formation of burrs to reduce the dependence on the deburring process. For this purpose, studies are carried out to reduce burr formation in the milling of various steel materials. Lin [20] has shown that there can be five types of burrs on the edges of the workpiece, depending on the cutting conditions when face milling one end of stainless steel. Silva et al. [21] analyzed the effect on the burr height at the side edge of the piece in machining of PH13 8 Mo stainless steel. They found that the height of the burrs was greatly affected by the shape of the cutting tool and the radial cutting depth, but not by the method of applying coolant. Saha and Das [22] conducted a front milling machine test with an additional bevel at the trailing edge of the workpiece to minimize the formation of burrs on the steel block during drying. They observed the slightest trailing edge with a trailing edge tilt angle of 15 °. Heisel et al. [23] found that lubrication reduced the amount of burrs and that cutting speeds at constant feed rates did not significantly affect burr formation. They also reported that the height of the burrs decreased as the angular radius of the tool increased.

The literature focuses on cutting resistance, surface roughness and cutting parameters on tool wear, cutting tool quality, and the effects of cutting fluids when machining a variety of stainless steels. However, research on AISI 304 stainless steel milling machines is limited, and this study investigated the effects of dry cutting conditions. On the other hand, the high segregation, mixed crystal structure, microstructure, and oxide-containing materials of cast stainless steel make their machinability difficult. This work looked at how different cutting settings and circumstances affected surface roughness and burr development when milling stainless steel AISI 304.

2. Material and Method

2.1. Features of workpiece and milling tool

AISI 304 material with dimensions of 50x80x50 mm was used in the milling tests. The composition of the test sample is given in Table 1. XNKT 080508 PNER ML PC5300 with cemented carbide pilot insert, produced by Korloy company, is designed for milling of AISI304 cast stainless steel. The inserts have TiAlN PVD coating and M30 ISO quality. EM90 XN08 D32 C32 L150Z2 designation tool holder was used.

Table 1. Chemical composition of AISI 304 test sample, %

Cr	Ni	Mn	Si	C	V
17.383	8.478	1.182	1.065	0.062	0.069
Cu	**P**	**S**	**Mo**	**Al**	**Fe**
0.321	0.034	0.015	0.431	0.003	70.84

2.2 Cutting conditions and experimental setup

The tests have been executed on a Taksan TMC-500V using three cutting speeds (100, 130, and 160 m/min), three feed rates (0.1, 0.15, and 0.2 mm/mouth), and constant cutting depth of 2 mm. Machining experiments were carried out by applying dry and mist cold air. A mixture of air and 5% K102-Force semi-synthetic oil was used at 6 bar pressures in mist cooling processing.

The experimental system includes investigating the effects of machining parameters on Ra and burr formation in dry and mist cold air processing of AISI 304 stainless cast steel at different cutting parameters. The experiments were firstly carried out with the down milling method using carbide cutting tools at the cutting parameters determined under dry machining conditions. Then, the same cutting parameters were carried out using the Frigid-X Sub-ZeroVortex mist cooling system. Experiments were repeated using a new cutting tool in each experiment to ensure reliability (Figure 1).

After the milling process, the Ra measurement was made with Mahrsurf M300 roughness device from six different regions of the surfaces and the average of them was taken. Afterward, photographs of the processed test specimens were taken and the burrs formed on the edges of the machined surfaces were examined with a Nikon SMZ745T tool microscope. The burrs formed on the machined edges were magnified 0.67x under an optical microscope and the burr heights were measured using the Clamex

Captiva software (Figure 2) and the evaluations were made by taking the average of the obtained data.

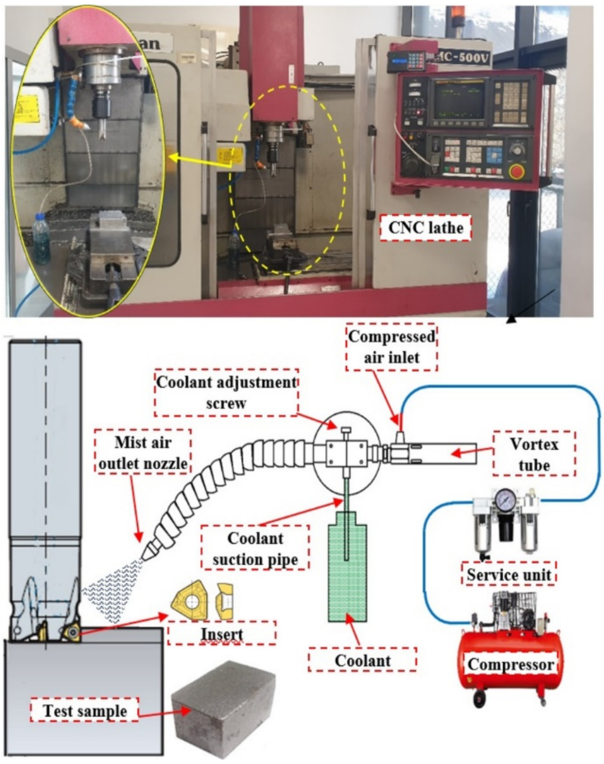


Figure 1. Experimental setup

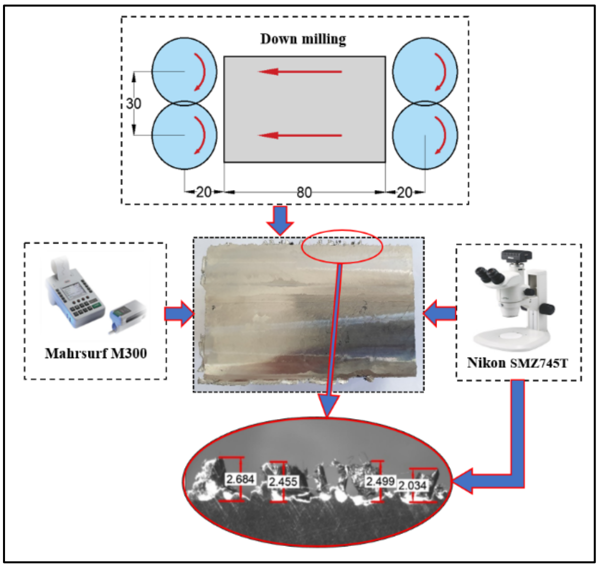


Figure 2. Measurement of Ra and burr height

3. RESULTS AND DISCUSSION

3.1. Evaluation of surface roughness

The Ra is evaluated using dry air and mist cold air (MCA) while milling stainless steel AISI 304 under various machining conditions and displays the Ra value obtained. Figures 3 and 5 demonstrate this. It is well understood that raising the feed rate raises the Ra value. Another machining metric, Ra, is projected to improve as cutting speed increases. The graphic in Figure 3 shows that the Ra value changes when the feed rate increases. The roughness value decreases at the feed of 0.15 mm/tooth as the cutting speed increases proportionally. Under dry machining circumstances, the smallest Ra was reached with 0.15 mm/tooth feed and a cutting speed of 160 m/min, whereas the highest Ra was achieved with the same feed and a cutting speed of 100 m/min.

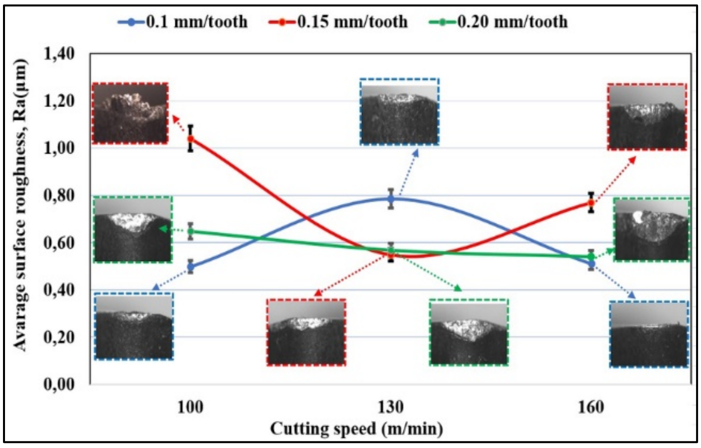


Figure 3. Variation of Ra versus cutting speed in dry milling

With a feed rate of 0.1 mm / tooth, raising the cutting speed from 100 m/min to 130 m/min improved the Ra value by about 52%, while increasing the cutting speed slightly decreased the Ra value. The irregularity of the microstructure of the material, the hardness towards the high surface of the material, and the production of irregular landmarks (BUEs) owing to the interaction of feed and shear due to the ductile nature of austenitic stainless steel might all explain this Ra tendency. The greater BUE production at lower cutting speeds utilizing the feed medium enhanced the Ra, as shown in the tool picture in Figure 3. With the feed of 0.15 mm/tooth and a cutting speed of 100 m/min, a maximum Ra of 1.04 µm was obtained. Ra values were lowered by 89% and 24% when the cutting speed was increased to 130 and 160 m/min, respectively. Increasing the cutting speed raises the temperature of the cutting zone, which reduces the likelihood of BUE [24] and allows for more stable cutting. When the cutting speed was increased from 100 to 130 m/min with a feed rate of 0.2 mm/tooth, the Ra value climbed by 14 percent, and at 160 m, the Ra value increased by 26 percent. The minimum cutting speed was observed. This increase in Ra is caused by cutting tool wear caused by the interplay of high feed rates (Figure 4).

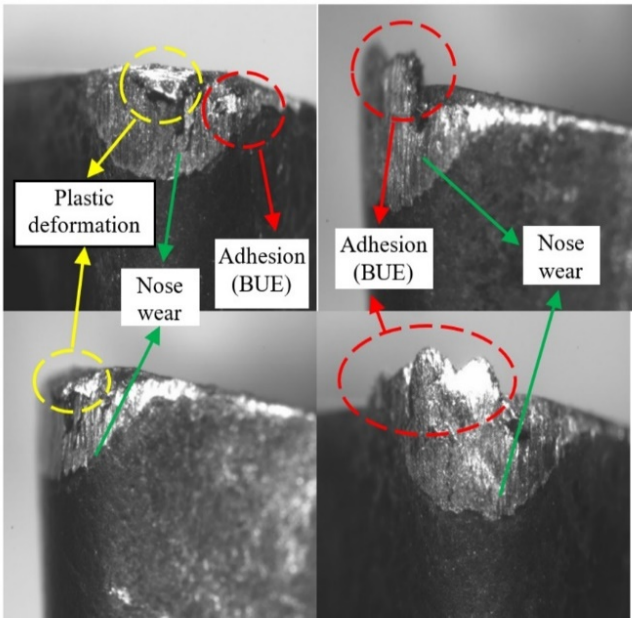


Figure 4. Tool wear images at 160 m/min cutting speed and 0.2 mm/tooth feed; a) Dry cutting, b) MCA

Figure 5 shows graphs of average Ra values acquired when milling AISI 304 stainless cast steel with mist cold air (MCA). When machining with MCA at a cutting speed of 100 m/min and a feed rate of 0.2 mm/min, the lowest Ra value is obtained, while the greatest Ra value is obtained at the same cutting speed and 0.15 mm/tooth feed rate of this result was obtained. In the MCA condition, the Ra value fluctuates based on the interaction between cutting speed and feed, just as it does in dry cutting. At a cutting speed of 130 m/min, the Ra values measured for all feeds are visibly near each other.

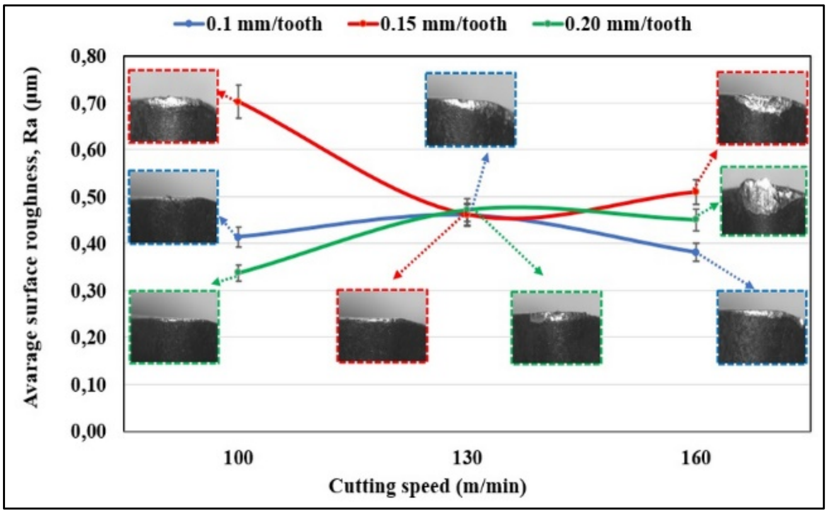


Figure 5. Variation of Ra versus cutting speed in MCA milling

Ra is 0.414 µm at 0.1mm/tooth feed and 100m/min cutting speed. When the cutting speed was increased to 130 m / min, the Ra value increased by 41% to 0.702 µm, then reduced to 0.337 µm when the cutting speed was increased to 160 m/min. This Ra trend is generated by a rise in cutting speed, resulting from an increase in cutting resistance and a decrease in chip adhesion to the cutting edge [25]. The Ra value at 0.2 mm/tooth feed is like the Ra value at 0.1 mm/tooth feed, indicating a similar trend. Surface quality degraded owing to cutting tool wear, which increased BUE when paired with high cutting and feed rates, similar to the results in a dry cutting environment. Raising the cutting speed from 100 m/min to 130 m/min at 0.15 mm/tooth feed raised the Ra value by 40, increasing the roughness value significantly at 160 m/min. This rise is thought to be caused by machine vibration [26] and tool wear, which can increase with increased cutting speed, as seen in Figure 4.

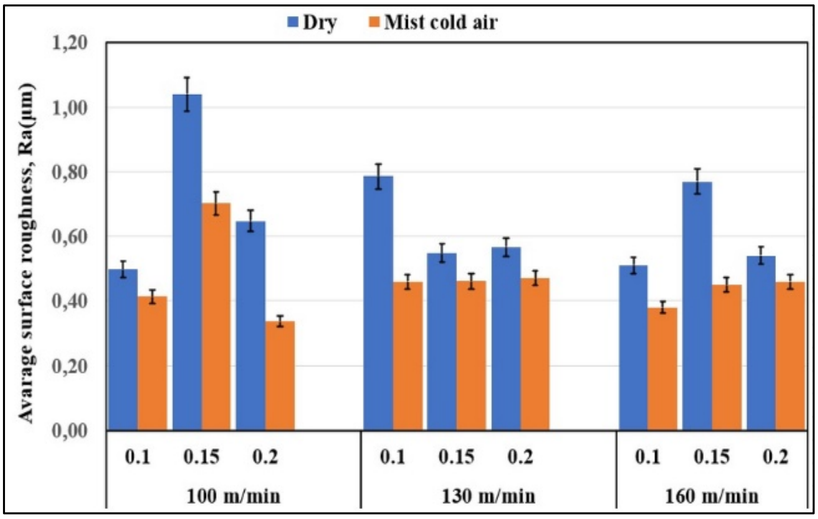


Figure 6. Comparison of the effect of cutting conditions on Ra

Figure 6 compares the Ra values obtained by milling AISI 304 alloy under dry and MCA cutting conditions. It was found that the Ra value obtained under MCA treatment conditions was lower (16% 48%) than the Ra value obtained by dry treatment. The greatest improvement was obtained at a cutting speed of 100 m/min and a tooth feed of 0.2 mm, which resulted in a 48 percent decrease. At a cutting speed of 100 m/min, an improvement of 0.1 mm/tooth feed compared to dry machining was attained, as well as an improvement of 0.15 mm / tooth feed compared to dry machining. At cutting rates of 130 m/min, reductions of 41 percent, 16 percent, and 17 percent were recorded at each feed level. Wrinkles were found at 0.1 mm / tooth feed 26%, 0.15 mm / tooth feed 41%, and 0.2 mm / tooth feed 15% at a cutting speed of 160 m / min. The MCA application leverages its lubricating function to minimize friction at the tool tip contact, and its cooling function reduces tool wear [27], allowing for the development of shorter tip forms. Therefore, reducing the thermomechanical effect at the tool tip interface reduces the BUE formation and makes the cutting process more stable. As a result, lowering the temperature of the cutting shadow in MCA applications improves tool wear, tip coating, and surface roughness. Alternatively, it is thought that the fluctuations in the Ra are caused by the casting method of the workpiece. After the casting process, it is seen that different inclusions and reoxidation residues are formed because the casting cooling rate is low and takes place under normal environmental conditions (Figure 7). The remaining particles created by the interaction of the liquid metal with the air at any step of the casting process are referred to as reoxidation residue [28]. Reducing the quantity of residue created by minimizing the interaction of the liquid metal with the air at all stages of the casting process.

When the workpiece's EDX analysis is evaluated, residues such as Cr_2O_3, FeO, MnO, and MoO_2 are seen. Because the structure of these residues is exceedingly rigid, they produce quick tool wear and changes in cutting forces during machining, hence worsening Ra. In addition, the hardness on the surface of the workpiece varies between 28-31 HRc, and it is thought that this hardness change triggers the fluctuations in Ra by affecting the outputs of the cutting process (chip formation, cutting force and tool wear).

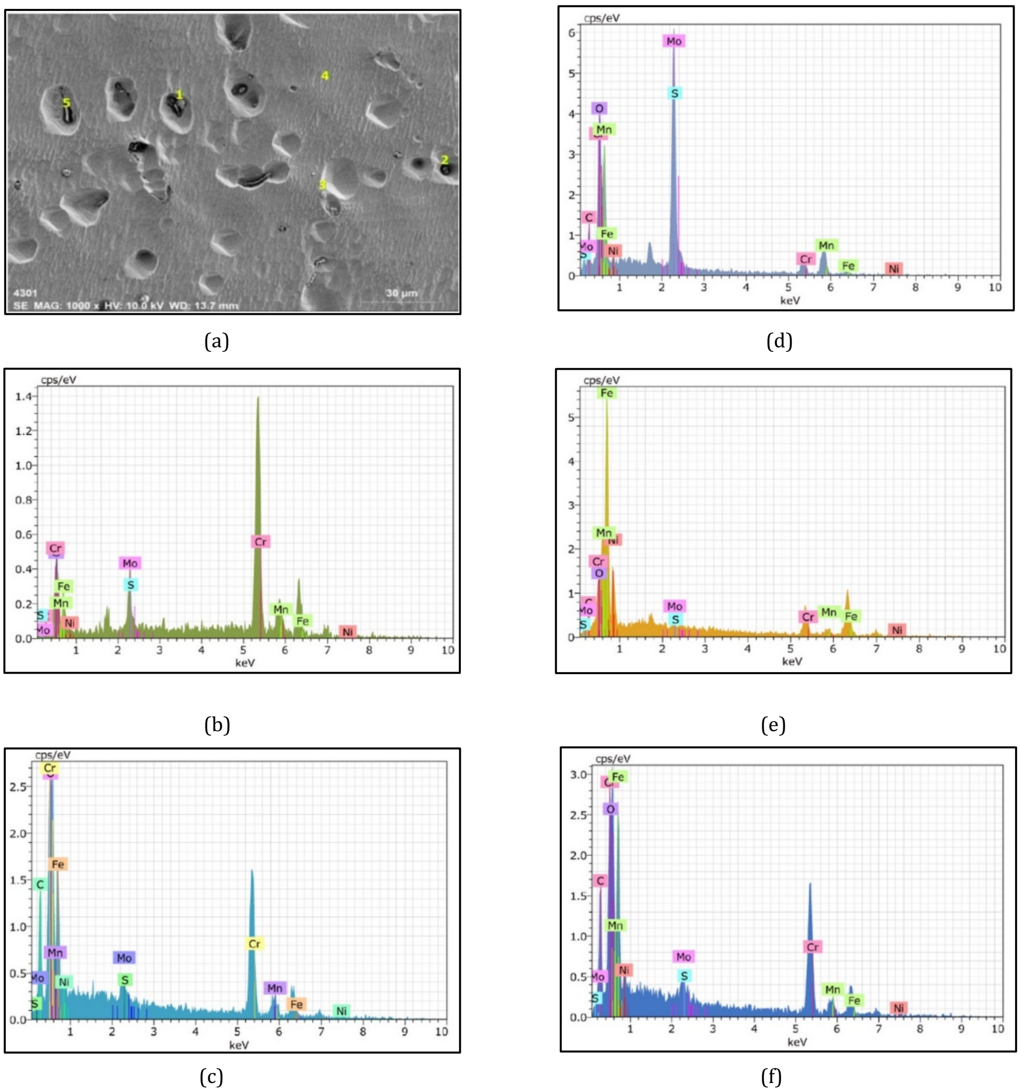
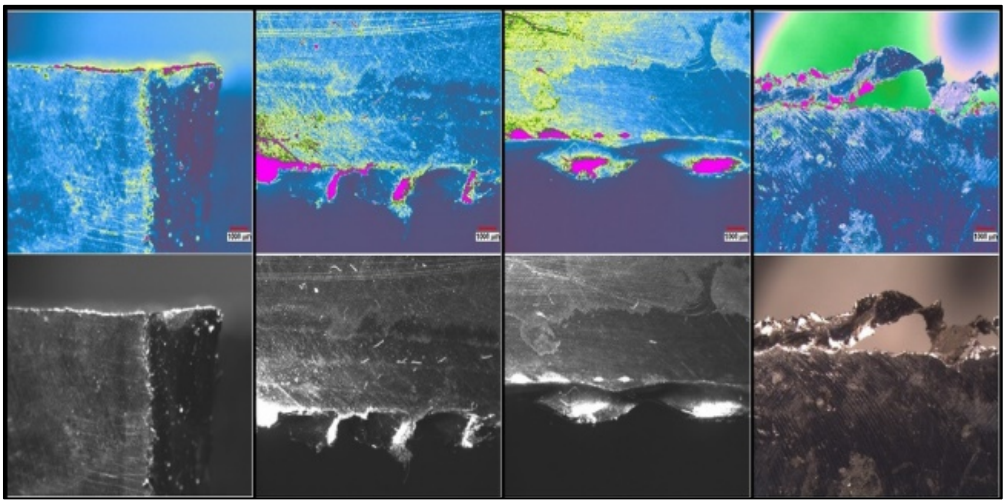


Figure 7. EDX analysis of the sample (a) Spectrum points, (b) Spectrum 1, (c) Spectrum 2, (d) Spectrum 3, (e) Spectrum 4, (f) spectrum 5

3.2. Evaluation of Burr Formation

Cutting speed, feed rate, cutting depth, workpiece shape, and cutting tool are all variables that influence burr growth on the front mill, and these qualities affect burr size and morphology. This study evaluated the types and heights of burrs formed under various cutting conditions. The height of the burrs and the thickness of the burr roots are used to calculate the size of the burrs.

Figure 8 depicts the burr types created during milling of AISI 304 alloy under different cutting conditions and machining environments. Burrs were generated on the edges of the workpiece after milling at the entry and exit of the cutting tool to the workpiece. When the types of burrs formed on the workpiece were examined, it was observed that knife type, saw, wave and burr-breakage burr types were formed and these burr types were similar to the burr types obtained in previous studies [20].

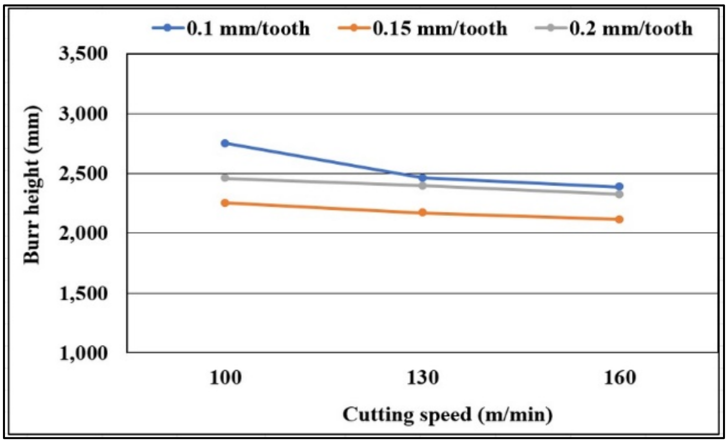


(a) (b) (c) (d)

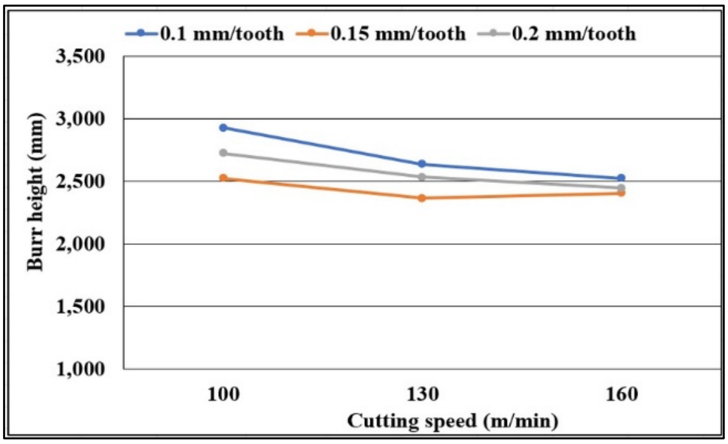
Figure 8. Types of burrs (a) Knife type (b) Saw type (c) Wave type (d) Burr breakage

It has been observed that knife-type burrs are generally formed at the entrance of the cutting tool to the workpiece in dry and MCA machining. This type of burr is formed by pushing out the uncut workpiece material when no chips are formed in the cutting tool. Saw-type burrs are similar to knife-type burrs, but they are a type of burr that occurs due to a small amount of breakage of the cutting tool edge. This sort of burr was most common in dry machining at high cutting speeds (160 m/min). The wavy burr is created by force applied to the material during the burr formation process. As a result, the top burr length is greater than the actual length of the machined edge, forcing the burr to take on a wavy form. In general, wavy type burr development was found at a feed rate of 0.1 mm/tooth in the studies. Burr breakage happens when a break in the center of the burr occurs, resulting in burr separation. Burr breaking usually happens after the second pass cutting process, independent of feed rate. In the dry machining condition, the ductility of the material increases as the temperature rises, usually in the low feed-high cutting speed interaction, which causes burr breakage at the edge of the workpiece.

The graphs depict the changes in burr heights caused by milling AISI 304 stainless cast steel as a function of feed rate, cutting speed, and machining parameters (Figure 9). Figure 9a depicts the effect of cutting speed and feed rate on burr height in dry machining, whereas Figure 9b depicts the effect in mist cold air (MCA) machining. The burr height created at 0.1 mm/tooth feed is greater than the other feed rates in the dry machining condition. Especially in the processing of ductile materials, because the chip volume removed at a low feed rate is less, chips with thinner sections are formed [28] and cause an increase in burr height. However, it is seen that the burr heights are higher at 0.2 mm/tooth feed rate than 0.15 mm/tooth feed. During milling, the feed per tooth defines the height of uncut chips [29], so as the feed increases, the thickness of uncut chips rises and the height of burrs rises as well. Under dry machining conditions, minimum burr heights were achieved with cutting speeds of 0.1 mm / min and 100 m / min, and maximum burr heights were achieved with 160 m / min and 0.15 mm / tooth feed. Looking at Figure 8b, the height of the burrs formed during MCA processing is similar to the height of burrs formed during dry processing. When machined with MCA, the most significant burr height is attained with a cutting speed of 100 m / min and a feed of 0.1 mm /tooth, and the lowest burr height is achieved with a cutting speed of 160 m / min and a feed of 0.15 mm / tooth.



(a)



(b)

Figure 9. Burr heights (a) Dry milling (b) MCA milling

When we examine the effect of cutting speed on burr height, we can observe that as the cutting speed rises, the burr height lowers. As the cutting speed increases, the friction at the cutting tool contact decreases, allowing plastic deformation and reducing chip thickness. As a result of the thermomechanical interaction in the second deformation zone, the plastic stress during chip formation is reduced [29]. This decrease affects the shape and size of the ridges that develop. High cutting temperatures at high cutting speeds, on the other hand, enhance tool wear and ductility, which has a negative impact on burr development. As is clear from Fig. 9, raising the cutting speed to 160 m/min reduced the tendency of the burr height to decrease.

When the burr heights obtained in dry and MCA cutting conditions are compared, it can be seen that lower burr heights occur in machining with MCA (Figure 9). A 5-10% drop was seen at 100 m/min cutting speed, 5-8% at 130 m/min cutting speed, and 5-12% at 160 m/min cutting speed. The high cutting temperature that happens at fast cutting speeds affects the material's flexibility and the creation of burrs [19]. MCA treatment had a good influence on burr development by lowering the cutting temperature. The applied cooling/lubrication method provided an average of 9% reduction in burr height. This result shows that the deburring operations after machining will be minimized with the cheap and easy-to-apply MCA method.

4. Conclusions

In the milling of AISI 304 steel, the interactions of numerous machining settings with surface roughness and burr height were investigated, and the results are presented below.

- Hard impurities in AISI 304 stainless casting steel structure caused rapid tool wear and aggravated Ra.
- When compared to dry machining, Ra improved by 15% to 48% during the face milling process with MCA application.
- In milling AISI 304 stainless cast steel, different burr forms such as blade, wavy, saw and burr breakage were formed on the workpiece.
- In dry and MCA cutting conditions, the burr height grew as the feed rate increased, whereas the burr height reduced as the cutting speed increased.
- In processing AISI 304 and similar materials, the mist cold air method is recommended for industrial applications in terms of good surface quality and minimum burr formation.
- The effects of machining conditions on the corrosion resistance on machining of AISI 304 stainless steel can be investigated in future studies.

Conflict of Interest Statement

The authors declare that there is no conflict of interest

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