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Effect of Cutting-Edge Geometry on the Machinability of 316l Austenitic Steel

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ABSTRACT

The paper focuses on the problem of selecting the correct tool geometry in high-speed milling of 316L stainless steel. Carbide milling cutters with two configurations of helix angle (40/42 degrees for tool#1 and 35/38 degrees for tool#2) with different cutting edge radiuses r_n (i.e. 4 µm, 6 µm, 8 µm, 10 µm and 12 µm) were prepared and their impact on cutting force and roughness were analyzed. The obtained results revealed that the small changes in cutting edge radius r_n have a significant effect on both cutting forces and surface roughness.In this context, irrespective to the type of the tool, increasing the cutting edge radius results in further cutting force. However, increasing the cutting edge radius shows different behavior on roughness while using different tool helix angles. For the tool#1, it was found that the surface roughness increases by increasing the cutting edge radius from 6 µm to 12 µm; while in the samples machined by tool #2, increase in cutting edge radius results in reduction of roughness. It was also found that irrespective to the values of cutting edge radius, the cutting force while using tool #1 is slightly less than the tool#2. In addition, the induced milling surface roughness of the samples machined by tool#2 is significantly less than the tool#1 where the mean value of Ra was reduced from 2.55 µm to 0.35 µm.

Keywords: milling, stainless steels, carbide tools, tool geometry, cutting edge radius

INTRODUCTION

Stainless steels comprise a group of alloys with diverse chemical compositions and mechanical properties, exhibiting various microstructures such as ferritic, martensitic, austenitic, and austenitic-ferritic. Furthermore, these alloys possess distinct physical properties. However, they share a common feature - a chromium content of over 11%, which imparts exceptional corrosion resistance [1]. The corrosion resistance primarily drives the widespread utilization of stainless steels across different industrial sectors including automotive, aerospace, medical, and food industries [2, 3]. One of the most widely used and available on the market austenitic stainless steel is 316L type [4, 5]. The machining of stainless steels through cutting processes holds significant importance in the mechanical industry. Advanced technologies and methods are employed to achieve create precision and complex (free surface) products. Given that stainless steels are utilized in demanding and harsh environments, the selection of appropriate machining conditions becomes crucial. The machining operations must adhere to industry requirements, ensuring satisfactory performance, accuracy and cutting tool life. The cutting process of stainless steel, especially in roughing operations, necessitates the utilization of suitable cutting tools. In many cases, tools designed for a general group of steels , such as stainless steels, may not fulfill the requirements of customers when specific grade of is machined. Therefore, selecting the appropriate tool for the specific type of material, in this case 316L stainless steel, becomes crucial. Relying on tools designated by manufacturers for a broad group of material often leads to excessive wear and unsatisfactory machining performance and quality. To achieve optimal machining results, it is necessary to choose tools tailored to the dedicated material type.

To achieve the highest quality in the milling process of stainless steel, it is crucial to apply suitable cutting parameters, including feed rate, cutting speed, and depth of cut [6]. Optimal selection of these parameters is undoubtedly critical, though it is essential to recognize that they are just one component influencing the overall machining process. Another important aspect of process design is the appropriate choice of the cutting tool. The right cutting tool selection plays a crucial role in ensuring efficient and precise machining results. The carbides are mainly used as tool materials, accounting for about 53% of all tool materials used. These materials are popular because of their strength and ease of shapeability in the grinding process. The second group of tooling materials includes tools made of high-speed steel are still widely utilized, accounting for approximately 20% of the market share, primarily due to their relatively low production cost. Approximately 19% of tooling materials are ceramics, PcBN and PCD [7]. To enhance the tool life of carbide cutting tools used for machining stainless steels, the additional coatings are applied primarily through CVD (chemical vapor deposition) and PVD (physical vapor deposition) methods. These advanced coating technologies are employed to improve the properties of the cutting tools, particularly by increasing their hardness, wear resistance, and oxidation resistance. By applying these coatings, the performance and durability of the carbide cutting tools are significantly enhanced. The use of such coatings has become a standard practice to optimize the efficiency and tool life of cutting tools in stainless steel machining processes. As research shows, in the process of shaping cutting tools, special attention should be paid to the preparation of the cutting edge [8, 9].

The preparation of cutting edges plays a crucial role in eliminating defects such as cracks, grain breakout and burrs that may occur during grinding process. Furthermore, this preparation process enhances the bond strength of the coating and increases the overall strength of the cutting edge, resulting in improved stability and an extended tool life. A significant aspect of this preparation is achieving the proper microgeometry of the cutting edge, which should have a smooth profile to minimize thermo-mechanical loading. The appropriate design of the microgeometry of the cutting edge should be tailored to different workpiece materials, cutting parameters, and types of cutting tools, to achieve optimal cutting performance. By using mathematical modelling of the process, it will be possible in the future to predict how the geometric parameters of the tool impact on machinability [10,11,12]. By addressing these considerations, the machining process becomes more efficient, accurate, and capable of maximizing the life of cutting tools. Increasing the life of cutting tools during the roughing and finishing of 316L steel is of utmost importance due to the rapid process of tool wear. The stainless steel 316L is known to be a challenging material to machine, and the high ductility and high temperatures involved in the process can quickly lead to tool wear [13, 14].

Accordingly, prolonging the tool life is a cutting-edge topic for manufacturer of SS316L products aiming at minimizing production time, reduce tooling costs, and increasing efficient machining performance. However, it is not possible without employing proper cutting parameters, tool coatings, and optimized tool geometries. Therefore, design an optimal cutter geometry to enhance the tool life of is still an open issue that merits more studies in depth.

Following the problem statement, in this paper, an experimental study has been carried out to analyze the effect of cutting-edge geometry on the machinability of 316L austenitic steel. Here, the carbide tools with different helix angle configurations and edge radiuses have been prepared and used for machining of SS316L samples. The machinability indicators such as cutting force, surface roughness and tool wear were taken into consideration to identify the optimal tool design.

MATERIALS AND METHODS

In the present work, series of experiments have been carried out on stainless steel 316L in shape of blocks with dimension of 100 mm x 100 mm x 50 mm as schematically shown in Fig.1a. In order to find the effect of tool design on machinability indicators, 12 mm helical milling cutters with two different helix angles i.e. 40/42 degrees (tool 1) and 35/38 degrees (tool 2) were prepared.

angle of and five edge radiuses i.e. 4 μm, 6 μm, 8 μm, 10 μm and 12 μm were designed and then ground by Poltra Sp. z o.o. on a precision Otec DF drag finishing machine. The radiuses of cutters after finishing were measured using an Alicon microscope. Additionally, a standard catalogue tool with the same geometry was included as a reference cutter. All the tools were made from MK12 tungsten carbide and PCD coated. They have also constat rake and relief angles of 8° and 6°, respectively. Specifications of tools can be found in Fig. 1b.

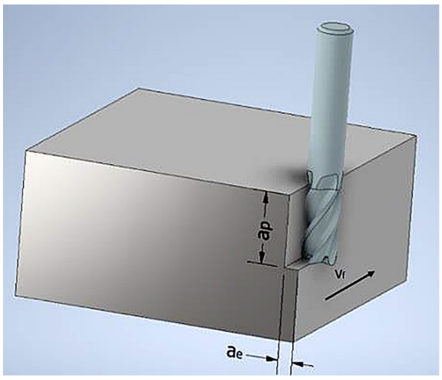
Effect of tool material on tool life (with configuration of tool 2) was also studied. Here, milling cutters with three different tungsten carbide grades namely MK12, GU20 and K10F have been prepared and their tool life was analyzed. The multipass milling experiments were conducted on rough machining regime with constant, the cutting parameters were kept constants on cutting speed V_c=100 m/min, feed rate V_f=679 mm/min, depth of cut a_p=24 mm, cutting width a_e=1.2 mm and four pass number.

The effects of tool design were investigated on main machinability indicators i.e., cutting forces, surface roughness and tool life. The cutting forces were measured using Kistler 9257B force measurement device. In order to analyze the cutting forces, their values on 2nd, 3rd and 4th pass were taken into account while the first pass milling test was intended to make the workpiece faces completely vertical compared to each other and remove the roughness reman from initial sawing operations. The measurement of surface roughness was conducted using a MarSurf PS device in the in the vertical (i.e. along the feed velocity direction) and horizontal (perpendicular to the feed velocity direction) in three randomly different points along the machining length. The tool life was quantified through analysis of the flank wear width VB. It was measured using an optical microscope at every minute and the tool was classified as worn, when VB reached the value of 0.2 mm.

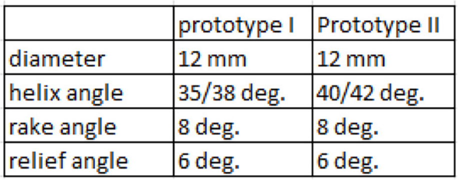
RESULTS AND DISCUSSION

Figure 2 illustrates force-time diagram for four-passes cutting which was measured for tools #1 and #2 under same value of cutting radius. It is seen from the figure that all the components of cutting force related to the tool #2 i.e. the tool with helix angle of 35/38 are significantly higher than the tool #1 i.e. with helix angle of

a)



b)



	prototype I	Prototype II
diameter	12 mm	12 mm
helix angle	35/38 deg.	40/42 deg.
rake angle	8 deg.	8 deg.
relief angle	6 deg.	6 deg.

Figure 1. Kinematics of the milling process (a) and difference between two types of tool geometries applied during tests (b)

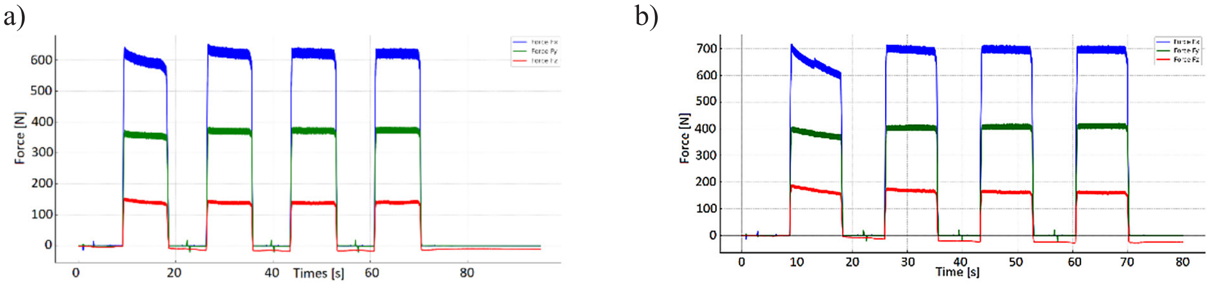


Figure 2. Example of cutting forces signal recorded during successive tool passes for tool 1 (a) and tool 2 (b); both tools with a cutting edge radius 6 μm

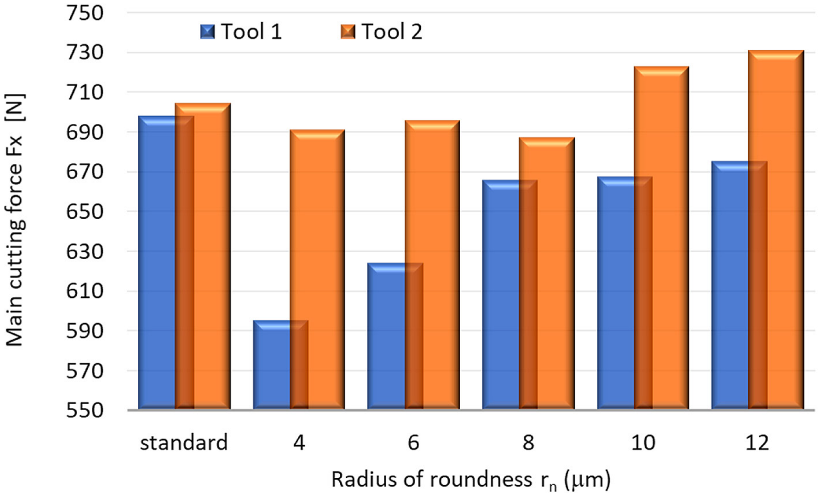


Figure 3. Influence of cutting edge's rounding radius r_n on main cutting force Fx values for both investigated types of tool

42/44 under same cutting edge radius. Moreover, Figure 3 presents a bar chart showing the cutting force values (F_x) for the different tools and under various cutting edge radius. It is seen from the figure that, for the tool #1, the increase cutting force significantly increases from 595 N to 698 N by increasing the cutting edge radius from 4 to 8 µm. However, by further increase of edge radius no more increase in cutting force values are observed. On the other hand, it is seen that increase of cutting edge radius doesn't have significant effect on amount of cutting force as the difference between the maximum and minimum values are about 44 N that is less than 5% of maximum cutting force. The bar graphs presented in Figures 4 to 6 consist of comparison of surface roughness parameter Ra measured in the vertical and horizontal directions to the feed velocity vector. As can be seen from these graphs, there are significant differences in surface roughness values and they are related to the type of tool used. Regardless of the value of cutting edge's rounding radius the Ra of the sample which were machined by tool #2 (i.e. with variable flute helix 35/38 degrees) are significantly lower than those processed by tool #1. It can be argued that, despite implementing roughing machining parameters, the surface roughness following the use of tool 2 falls within the 0.2-0.5 µm range that is even an acceptable value for finish-cutting.

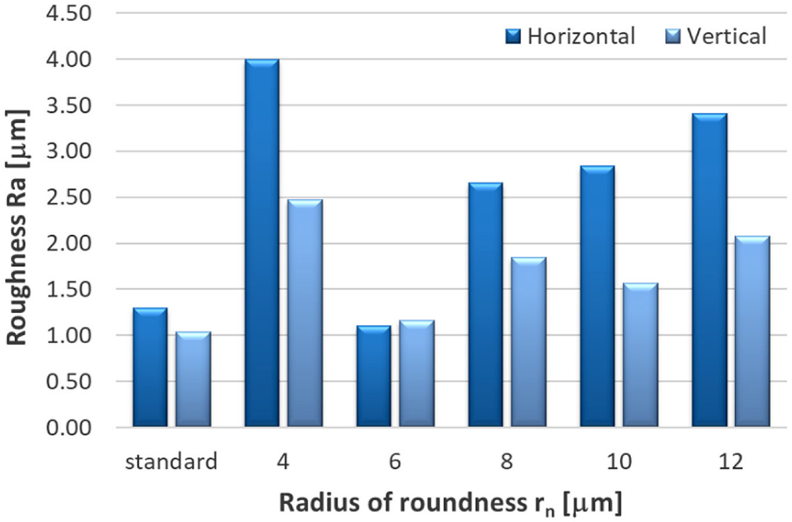


Figure 4. The surface roughness values (Ra) obtained during milling with tool #1 measured in both vertical and horizontal directions

It can be also seen from the presented results in Figures 4 and 6 that the cutting edge radius has more significant effect on cutting force and roughness when the samples are cut by tool 1. Moreover, as summarized in Table 1, for the samples milled by tool 2, the mean value of Ra measured in horizontal direction six times lower that those measured for tool 1. In addition, the

Table 1. The values of Ra for both types of investigated tool geometries (mean and standard deviation values calculated from the results obtained for machining with tools with different cutting edge's rounding radius)

Parameter	Tool #1 (flute helix of 40/42 deg)		Tool #2 (flute helix of 35/38 deg)	
Measure direction	horizontal	vertical	horizontal	vertical
Mean value [μm]	2.55	1.69	0.38	0.36
Std dev. [μm]	1.149	0.549	0.104	0.055

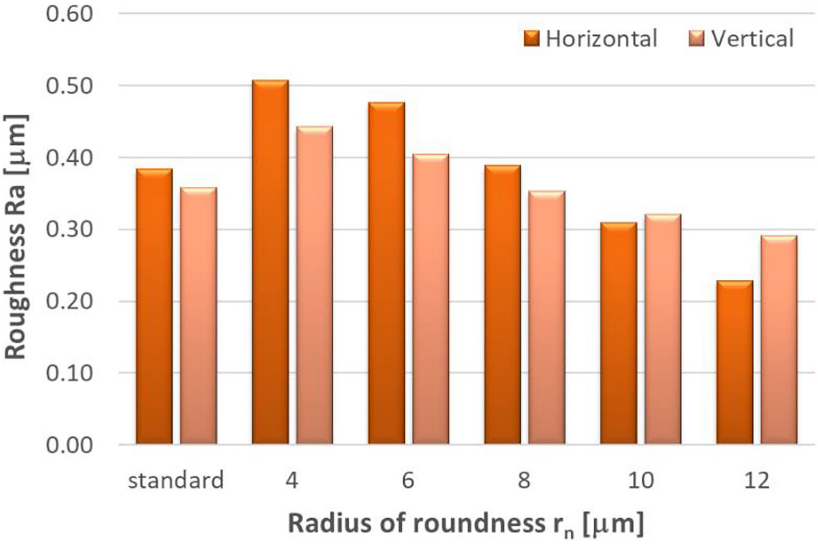


Figure 5. The surface roughness values (Ra) obtained during milling with tool #2 measured in both vertical and horizontal directions

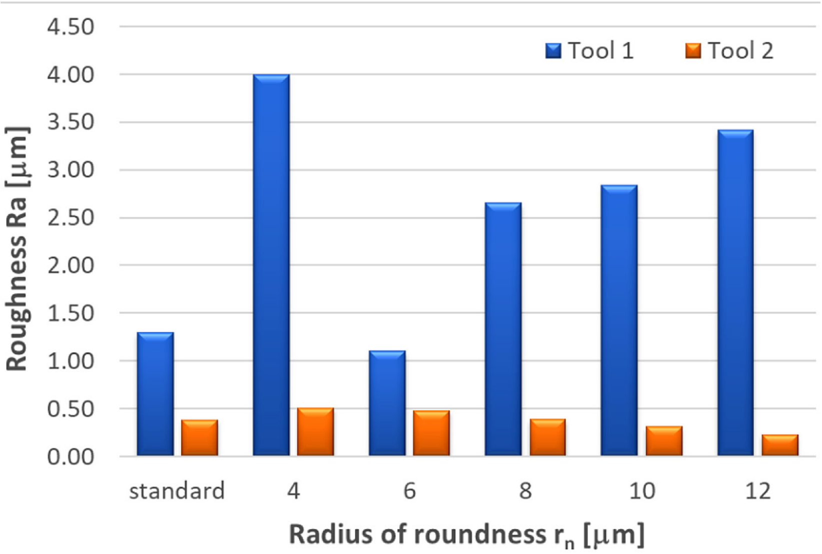


Figure 6. Compare the surface roughness values Ra obtained by milling with tool #1 and #2, measured in the horizontal direction

standard deviation of Ra measured in horizontal is almost 50% of its average value. This is confirmed by correlogram (F_x, Ra) presented in Figure 7. Calculated correlation coefficients between F_x and Ra are respectively: for tool 1 r_1=-0.345 and for tool 2 r_1=-0.87, which indicates that results of machining with tool 1 are more difficult to predict. The effect of helix angle on surface roughness can be attributed to its effect on as magnitude of the cutting forces. By changing the tool helix angle, the direction and value of the cutting forces are significantly changed and affect the tool vibration during milling process. accordingly, since the vibration has great impact on generation of milled surface roughness, change of helix angle improves the roughness value by minimization the amplitude of chatter vibration during milling process [15, 16]. The helix angle of the cutting edge also affects the speed and direction of chip removal from the cutting zone [17]. Therefore, the enactment of the surface roughness by changing the helix angle can be attributed to the reduction of chatter vibration amplitude together with improvement of the chip flow and minimizing occurrence of phenomenon like built-up-edge that has negative influence eon roughness values.

The impact of tool materials made of different types of tungsten carbide were studied on tool wear of milling cutters. The obtained results indicated that the type of tungsten carbide grade has significant influence on tool wear. Accordingly, MK12 carbide with the 0.18 µm grain size yields better tool life compared to GU20 carbide in machining of 316L stainless steel. The measured tool life for this tool was 180 min which was the best one among K10F with life time of 113 min and GU20 with life of 13 min. The results can be attributed to impact of tool material on ability of adjusting friction coefficient and vibration which was reported in [18].

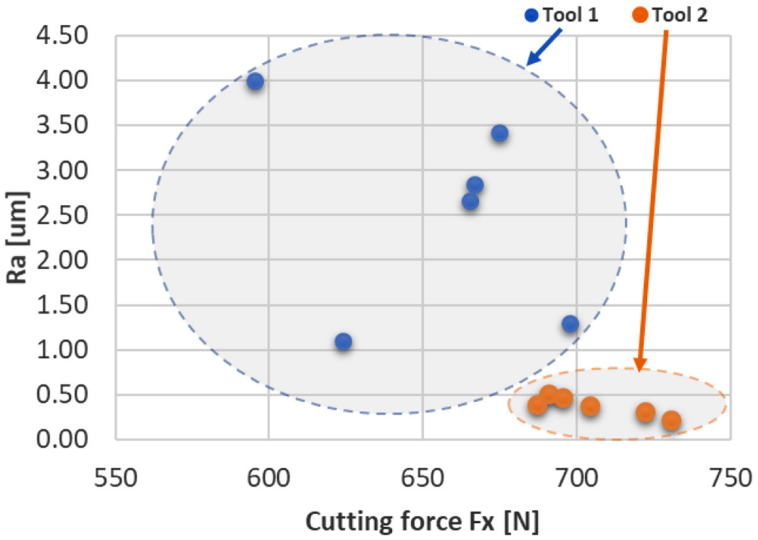


Figure 7. Relationship between main cutting force F_x and surface roughness R_a measured in the horizontal direction; summary of the results for tool #1 and #2

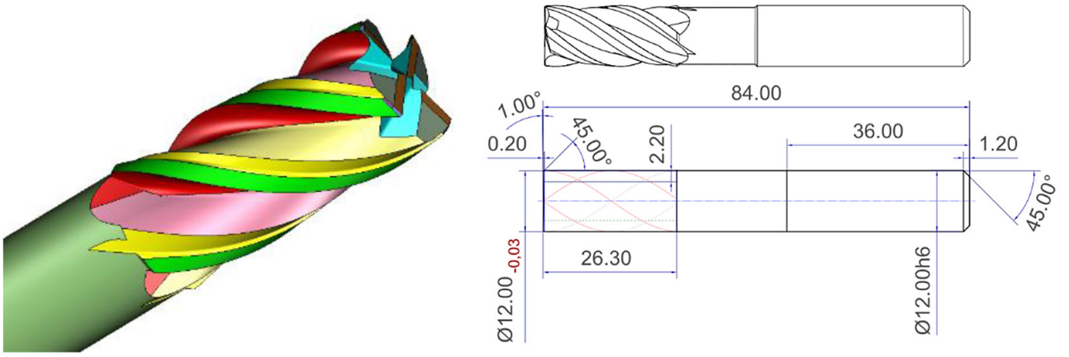


Figure 8. Visualisation geometrical and parameters of a milling cutter used in experimental studies

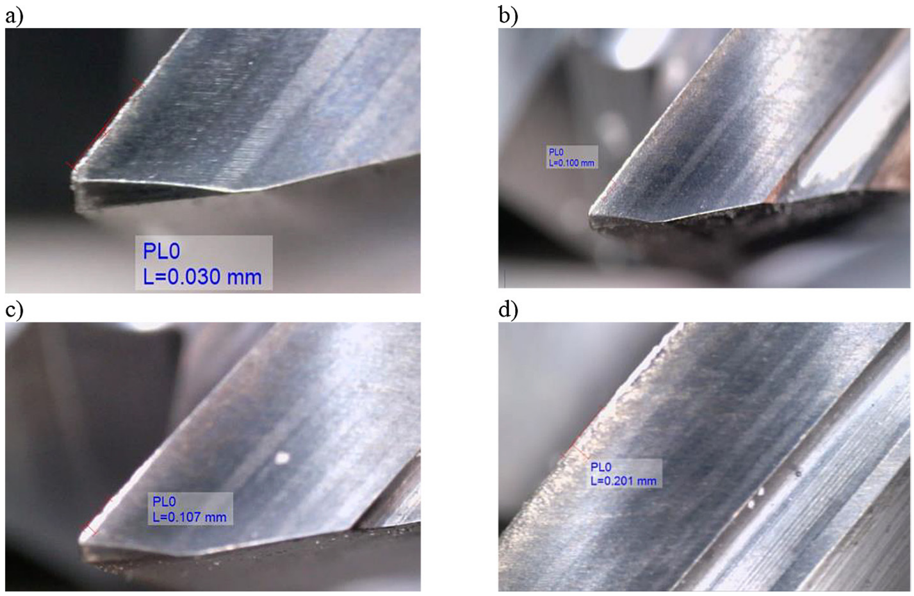


Figure 9. Wear at the cutting edge of a functioning tool was measured for four different periods of time (a) 3 minutes, (b) 60 minutes, (c) 90 minutes, and (d) 183 minutes (tool geometry presented in Figure 8)

CONCLUSIONS

In order to address the tool design effectiveness in machinability of stainless steel 316L, in presented study the effects of specially designed milling tool geometries with different helix angle and cutting edge radius were investigated on surface roughness and cutting force. The optimum tool in term of foresaid machinability indicator then coated with different carbide grades and its impact on tool life was studied in depth. The main aim of the study was to understand how small modifications in tool geometry can make a difference to quality and performance of machining process. The obtained results can be summarized .

The surface roughness after milling is significantly affected by the radius of the cutting edge and the helix angle. One can state that significant reduction in surface roughness can be achieved by modifying the helix angle. By changing the helix angle, because of reduction of chatter vibration amplitude, and restriction of formation of built-up edge as result enhancement of chip flow and cutting temperature, the surface roughness enhances. It was also found that the increase of cutting edge radius results in increasing the cutting force; while it has different impact on surface roughness variation with different tool helix angle. Accordingly, the interaction effect of helix angles and cutting edge radius has significant effect on roughness. It was also obtained that type of coating plays predominant role in determining the tool life where tungsten carbide coating with grade of MK12 results in 15 times more tool life compared to the grade GU20.

In industrial practice, the selection of cutting tool geometry plays a critical role in the machining process to achieve optimum performance, especially when machining difficult-to-machine materials such as 316L stainless steel. The results of the research presented show that the appropriate selection of cutting edge radius and helix angle of the milling cutter can effectively reduce surface roughness and manage cutting forces, leading to improved machining efficiency and product quality. This knowledge is particularly important in the design of tools and machining technology using dedicated monolithic carbide cutters designed for a specific application. Therefore, further research and development in this area could lead to significant advances in the machining of 316L stainless steel, and the results obtained can be an essential guide not only for technologists but also for manufacturers of custom-made special cutting tools.

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