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Machining of Austenitic Stainless Steels - the Influence of Various Factors on the Machining Result

Miroslav Čička [1*], Renáta Turisová [1], Ferdinand Kóča [1], Hana Pačaiová [1]

[1] Technical University of Kosice, Faculty of Mechanical Engineering, Department of Safety and Quality, Letna 1/9, 042 00 Kosice – Sever, Slovak Republic

Abstract: In today's world, AISI stainless steel accounts for almost half of the world's production and consumption for industrial purposes. Stainless steel is the most popular alloy widely used in the production of parts due to its properties such as high strength, high corrosion resistance or high ductility, but they are hard materials to machine from the metallurgical aspect, such as low thermal conductivity, chip formation, cutting tool wear. The focus of the paper is on machining stainless steel – a review, where various machining problems are discussed by different researchers and their probable solution can provide help to reduce tool wear, increase corrosion resistance, high surface quality finish by reducing machining complexity. The article also provides a detailed specification of the most important factors that significantly affect the lifespan of tools used for machining austenitic stainless steel.

Keywords: AISI 304; Machinability of Stainless-steel; Quality; Surface Integrity; Tool Wear

1. Introduction

Early use of stainless steel (SS) was limited to a few applications, such as nitric acid tanks. As various compositions were developed that made the steel highly resistant to corrosion even at elevated temperatures and gave it high strength, manufacturers began to use it for a greater number of applications. The advantages of stainless steel include easy cleaning and minimal maintenance, good corrosion resistance, durability, economy and hygienic design. Another significant advantage of stainless steel is its environmental friendliness. Compared to mild steel, it has a very long life and can be 100% recycled. As shown in Figure 1, the stainless steel family includes five basic types of steels according to their metallurgical structure: martensitic SS, precipitation hardened SS, duplex SS, austenitic SS, and ferritic SS [1].

Future industry relies on new design concepts and methods [3], data acquisition, processing, visualization, automation, and manufacturing technologies. Industry 4.0 (I4.0) is to undertake the challenges in integrating technologies like Cyber-Physical Systems, the Internet of Things, and the Internet of Services to advance improvements in industry [4-5]. With the increasing development of industrial production focused on sustainable industry (I4.0) and with the constant increase in demands on the functional and surface parameters of machined parts, the quality requirements of CNC machining centers are also constantly increasing. Their high productivity and quality of work is influenced by the technical level of the machining centers themselves.

The resulting quality product can be achieved only when the same tools of quality management at all levels are applied in horizontal cross-linking of production and logistic structures. Based on the basic idea of the Industry 4.0 Strategy is the

*** Corresponding author:** Miroslav Čička, ***E-mail address:*** *mirko.cicka@gmail.com*

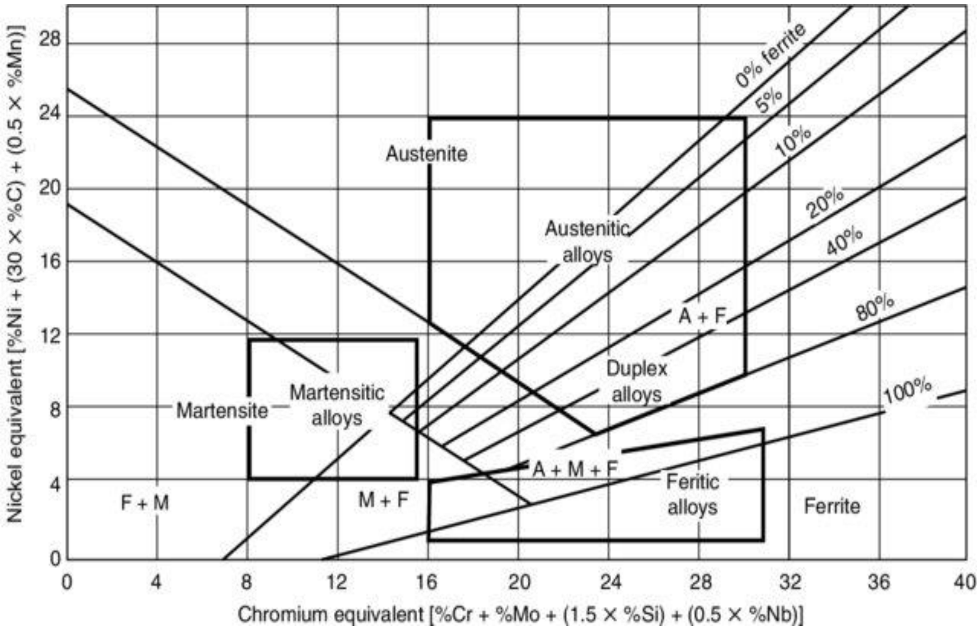

Figure 1: Schaeffler's constitution diagram for stainless steels [2].

perception of the complexity of this philosophy, which involves all parts of the chain for the flow of information, linked to specific manufacturing and assembly workplaces. The final product delivered to the customer in accordance with the requirements encompasses several aspects. These are the areas through which the philosophy of the strategy Industry 4.0 can be applied in the real production [6].

The quality of the work, the production of geometrically and dimensionally accurate products in the prescribed accuracy class is what is expected of the current production system. To enable any manufactured product to correctly perform its function for which it is intended, its actual shape and surface may differ from that of the ideal component, but only within certain permissible limits. These geometric deviations occur due to the influence of various factors that act permanently or temporarily during the manufacturing process [7]. One of the most valued quality requirements in machining processes is related to the concept of surface integrity (SI). It is defined as the inherent or enhanced condition of a surface created by machining operations or other surface-forming processes. Resp. SI is a set of properties (both surface and deep) of an engineering surface that influence its operational behavior. These properties include geometrical, physicochemical, and biological parameters [8].

Kaladhar et al [9] defined SI as a set of properties that the surface of a material exhibits, acquires or becomes modified during the forming process. These properties can be analyzed from three points of view: micro geometric (surface roughness, micro and macro cracks, waviness, particle adhesion), macro geometric (cylindricity, concentricity, straightness, roundness) and physicochemical properties (micro hardness, residual stress, corrosion under stress, strength in traction, fatigue behavior). The authors pointed out that these properties can not only improve the functional performance of the part, but also worsen it.

High-speed machining is gaining popularity in industry in recent years due to its capability to improve machining performance, reduce costs while achieving reduced lead times and higher productivity. The requirement for high quality focuses attention on the condition of the surface and the quality of the product, especially on the roughness of the machined surface, because it affects the appearance, function, and reliability of the product. In addition, a high-quality surface significantly improves fatigue strength, corrosion resistance and service life. Austenitic stainless steel is one of the "difficult to cut materials" and difficulties such as poor finish and high tool wear are common [10]. Korkut et al [11] and Ciftci [10] reported that when turning AISI 304 austenitic stainless steel, tool wear decreases with increasing cutting speed up to 180 m/min and surface roughness values decrease with increasing cutting speed [12-13].

Austenitic stainless steel (AISI 304) is the most versatile type of stainless steel and is widely used in various industries owing to its attractive properties. It is excellently weldable and has a high resistance to fatigue and oxidation [14]. AISI 304 stainless steel is a universal stainless steel with excellent, comprehensive properties, and it is one of the most widely used Cr-Ni series austenitic stainless steels. It has moderate strength and good ductility and corrosion resistance [15].

In machining, diverse materials under constant machining conditions and diverse cutting forces owe their origins to the different physical and chemical properties of a workpiece material. The properties of workpiece materials that may affect machinability are microstructure, grain size, heat treatment, chemical composition, hardness, yield strength, tensile strength and physical properties such as the modulus of elasticity, thermal conductivity, thermal expansion, and work hardening [16].

2. Metallurgy of austenitic stainless steel

Austenitic stainless steels contain chromium and nickel (and sometimes additionally manganese and nitrogen) to stabilize the austenitic microstructure. Austenitic stainless steels have certain properties due to a stable austenitic microstructure (good formability, weldability, ductility, excellent toughness, and non-magnetic characteristics). Due to the high content of chromium and nickel, it is also the most resistant to rust of all classes. Therefore, austenitic stainless steels have become the most popular and widely used of all groups of stainless steels in use today [1].

There are several applications in the world for structural and non-structural components made of stainless steel, all of which are alloys of iron, chromium, nickel and, to varying degrees, molybdenum. The characteristic corrosion resistance of stainless steel depends on the chromium content and is improved by the addition of molybdenum and nitrogen. Nickel is added primarily to ensure the mechanical properties and correct microstructure of the steel. Other alloying elements may be added to improve specific aspects of the stainless steel, such as high temperature properties, increased strength, or to facilitate specific processing methods [11].

The 300 series is based upon the classic 18% chromium and 8% nickel. It is the most used class worldwide. Here, nickel is used to produce the austenite structure and is responsible for its high toughness and strength at both high and low temperatures. Nickel also significantly improves oxidation and corrosion resistance. The 300 series classes also have "L" and "H" type subclasses. The L-type classes are designed for extra corrosion resistance. The letter L indicates a low carbon content (as in 304L, 316L), which is around 0.03%. It is used exclusively for welding. Class "H" contains a minimum of 0.04% carbon and a maximum of 0.10% carbon. This is recommended when using the material at extreme temperatures. The most used grade is 304. It consists of 18% Cr and 8% Ni. In terms of application, classes 300 cover various sectors such as the chemical industry, the food and dairy industry, or the aerospace industry [2].

To improve the machinability of austenitic stainless steels, it is necessary to add free machining elements such as sulphury, lead, selenium, tellurium, copper, aluminum, phosphorus. These elements help reduce friction between the workpiece and the tool [18].

3. Machining of austenitic stainless-steel

Machinability refers to the degree of difficulty of machining under specified conditions, which is expressed as a percentage. Austenitic stainless steels are considered the most difficult material to machine due to their high mechanical hardenability, high ductility and hardness, low thermal conductivity. In addition, the level of hardness, carbon content and nickel content also affect the difficulty of machining. While machining austenitic stainless steel, the choice of insert geometry, chip breaker geometry and feed rate must also be considered. To eliminate vibration, it is necessary to ensure adequate rigidity of the tool [16].

Because of the variety of stainless steels, their machinability ratings vary from low to high. Machinability is a quality characterized by the degree of difficulty of machining a metal working material under specified conditions. The machinability rating is expressed as a percentage, assuming a free-machining AISI 1212 carbon steel

Table 1: Chemical composition of Stainless-Steel Alloys [17].

Alloy	S30403	S31603	S31703	N08367	S44735	S32154
Fe	71.567	69.053	63.525	48.118	66.594	55.162
Ni	8.200	10.140	13.200	23.88	0.260	17.900
Cr	18.33	16.240	18.100	20.470	28.750	20.000
Mo	0.500	2.070	3.160	6.260	3.780	6.050
Mn	1.470	1.780	1.510	0.300	0.260	0.490
C	0.023	0.019	0.017	0.020	0.020	0.012
N	0.030	0.050	0.030	0.330	0.031	0.196
Si	0.380	0.280	0.460	0.40	0.280	0.350
P	0.030	0.027	0.027	0.021	0.023	0.019
S	0.0002	0.001	0.001	0.0003	0.002	0.001
Cu	0.460	0.340	0.150	0.200		0.680
Co		0.240				
Nb					0.290	
Ti					0.360	

machinability rating of 100%. If the machinability values of the work materials are less than 100%, such work materials are more difficult to machine than AISI 1212 steel. Low machinability is attributed to austenitic steels, including 302B, 309, 309S, 314, 329, 330, and 384. The machinability values for these steels are only about 40% of the value for free-machining AISI 1212 carbon steel. Low machinability is characterized by high tensile strength, large variance between yield strength and tensile strength, high ductility and toughness, high hardening rate, and low thermal conductivity. High machinability is attributed to ferritic steels 430F and 430F (Se), as well as martensitic steels 416 and 416Se. The machinability values for these steels are approximately 90% of that of the free machinable carbon steel AISI 1212 [11]. In general, austenitic steels are more difficult to machine. Several factors should be considered when machining austenitic steels (i.e. [1] or [19]:

– *The cutting tool absorbs more heat, which can cause the edge to build up; to consider is the cutting speed, the choice of positive insert geometry or use coated cermet grade.*
– *Chips are fibrous and tend to tangle, making them difficult to remove; possible solutions are a higher feed rate, a chip breaker geometry based on the nose radius of the insert or a smaller nose radius.*
– *Vibration occurs if the rigidity of the cutting tool is insufficient.*
– *Cut surfaces can be more difficult to the machine if cutting is interrupted or if the feed rate is too low.*

3.1 Surface integrity and Tool wear

During machining, the quality of the surface treatment is an important requirement, therefore the choice of optimized cutting parameters is very important for checking the required surface quality [20-22]. Machining difficult-to-machine materials such as AISI304 usually leads to poor surface finish, irregular tool wear and premature tool failure [23-24]. This is mainly due to high strength, high fracture toughness, high resistance to fatigue and corrosion. Low thermal conductivity, together with high strength and high heat capacity, make stainless steel a difficult material to machine. The hardenability of stainless steel, together with the mechanical and thermal properties, leads to severe tool wear and low quality of the machined surface. The surface parameter used to evaluate the surface roughness is the roughness average (Ra). The roughness average is the area between the roughness profile and its centerline or the integral of the absolute value of the height of the roughness profile over the rating length [25].

A set of parameters believed to affect surface roughness and investigated by the researchers is schematically shown in Fig. 2.

The extent of wear of the cutting tool depends on the material and geometry of the tool, the material of the workpiece, the cutting parameters, the

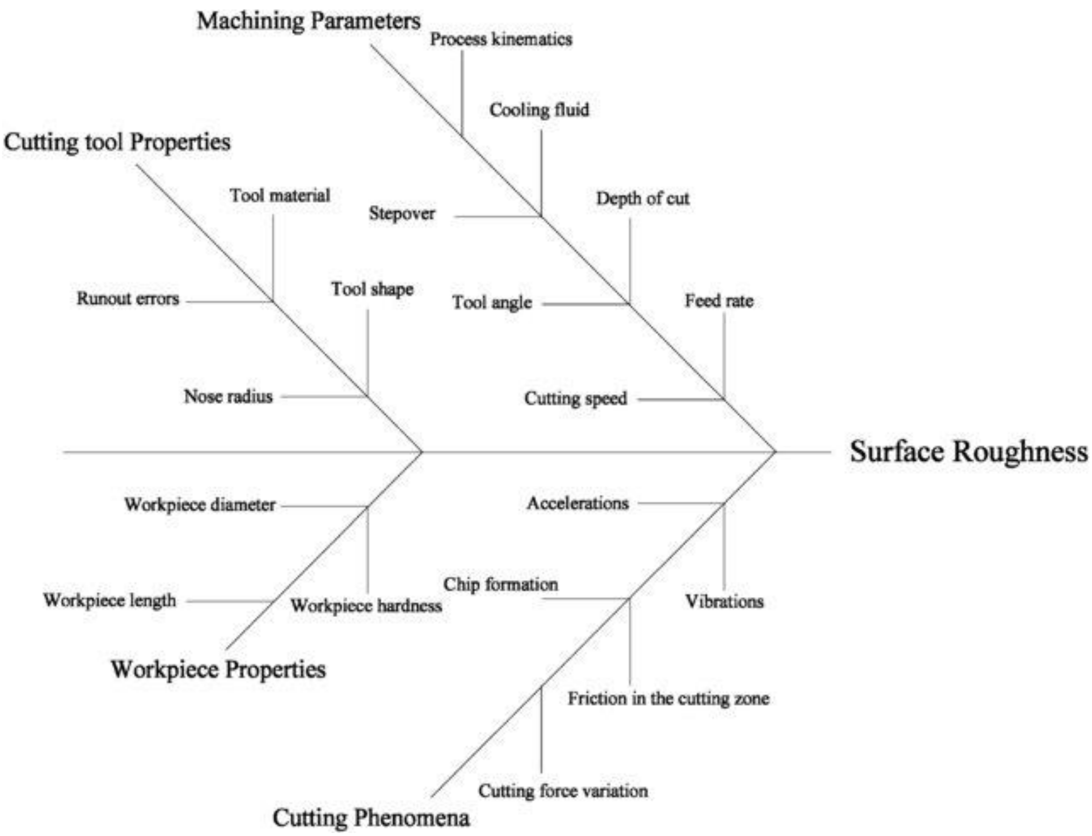

Figure 2: Fishbone diagram for Surface Roughness Parameters [25].

characteristics of the cutting fluids and the machine tools. Abou-El-Hossein and Yahya [1] noticed an increase in tool wear with increasing cutting speed, while a decrease in tool wear was simultaneously observed with increasing cutting feed. Tool life decreases with improper edge formation. So, edge preparation has an important effect on tool life. The principal cutting edge, which performs the primary work during turning, is formed by the intersection of the rake and the side flank surfaces. The intersection of the side relief and end relief surfaces produce the end cutting edge. The point at which the side and end-cutting edges converge is called the tool nose. It is the scrawniest part of the tool and determines the overall strength of the cutting edge. As a result, to increase its strength, the tool point is given a cutting edge that is circular or is in the form of a transitional cutting edge [11].

3.2 Literature review on machining of austenitic stainless-steel

Kuram et al [18] conducted experimental studies to determine the effect of vegetable-based cutting fluids on thrust force and surface roughness during drilling of AISI 304 austenitic stainless steel. The Taguchi method was used for experimentation, and mathematical models were developed from regression analysis to predict tool wear values and forces. It was observed that sunflower cutting fluid and canola cutting fluid were more effective in reducing tool wear and force than commercial semi-synthetic cutting fluids. Çaydas and Ekici [26] used support vector machine (SVM) tools, namely least square SVM, spider SVM, and artificial neural network (ANN) model to assess the developed surface roughness values of AISI 304 austenitic stainless steel. All models developed by SVM performed better than ANN models. A statistical paired t-test was performed to verify the results of the SVM and ANN models. The t-test results of the experimental findings showed the SVM spider as the most correlated pair. Tekıner and Yesılyurt [27] investigated the values of flank wear, energy consumption, surface roughness and chipping by considering acoustic emission (AE) during machining of AISI 304 grade. The results obtained from process sound were compared with classical methods. The work revealed that the change in cutting parameters also led to a change in sound pressure levels. Korkut et al [11] in their study determined the optimum cutting conditions for machining AISI 304 austenitic stainless steel as an attempt to determine the optimum cutting conditions for machining AISI 304 austenitic stainless steel. The researchers investigated the effect of speed on tool wear and surface roughness. They presented a correlation between tool wear, surface roughness and chips obtained at a selected speed. Al-Ahmari [4] developed models to predict material machinability, tool life, cutting force and surface roughness using RA, response surface methodology (RSM) and computational neural networks (CNN). To determine the best machinability prediction model, the relative error in percent was calculated. t-tests, f-tests and Levene's test were performed to compare the goodness of fit of the models. It was concluded that CNN is better than RA and RSM method in predicting machinability models. Li and Wu [16] investigated conventional austenitic stainless steel and free-cutting austenitic stainless-steel materials. Machinability tests were conducted to determine the effect of free-cutting additives and the results showed that the addition of free-cutting additives improved the machinability of the austenitic stainless steel as well as the tensile strength, yield strength and total elongation values of the material. Özek et al [28] conducted an experimental investigation on the machining characteristics of AISI 304 grade by varying the cutting parameters to investigate the effect on the tool-chip interface, surface roughness and flank wear. Depth of cut and feed rate proportionally affected surface roughness, while cutting speed had the opposite effect. It was observed that there was a decrease in the interface temperature with an increase in the cutting speed. Galanis and Manolakos [14] developed a surface roughness model using response surface methodology (RSM) when performing high-speed machining of AISI 316L. The results showed that depth of cut was the most significant factor and feed rate was insignificant. Sensussi [29] dealt with the microhardness behavior of chips with workpiece diameters of 30, 40 and 50 mm when turning AISI304 grade. RSM was used to develop statistical models to predict accurate chip microhardness. The obtained experimental results showed that the increase in chip microhardness took place at low cutting speed, high feed speed and cutting depth. Kaladhar et al [9] machined different compositions of austenitic stainless steels to analyze the effect of additives on the mechanical properties and machinability of the material. The goal was to obtain optimal cutting conditions for any type of austenitic stainless steel.

3.3 Machining problems observed from experimental findings

Common problems associated with the machining of austenitic stainless steels have been discussed in various publications. Due to the severity of these problems, which lead to poor machinability, these steels are classified as difficult-to-machine materials. In addition, many researchers claim to have observed certain phenomena encountered during their experiments, which they consider to be

Table 2: Austenitic stainless-steels – overview of machining problems.

Problem description	Source
The presence of macroparticles on the tool surface coating - difficulties to perform machining operations with these tools.	[30]
Inhomogeneous chip thickness distribution - responsible for poor surface treatment.	[12]
By using resulfurized steel, greater surface roughness is achieved.	[18]
Reducing the cutting speed, increasing the depth of cut and increasing the feed rate cause poor quality of machined surfaces. At lower cutting speeds, the performance of the tool is very poor.	[12-13] or [27]
The increase in austenite grain size is responsible for the deterioration of machinability.	[31]
Variations in the properties of different classes of austenitic stainless steels (due to changes in their chemical composition) affect their machinability.	[13]
Tool wear is adversely affected by liquid nitrogen, which lowers the temperature of the workpiece.	[18]

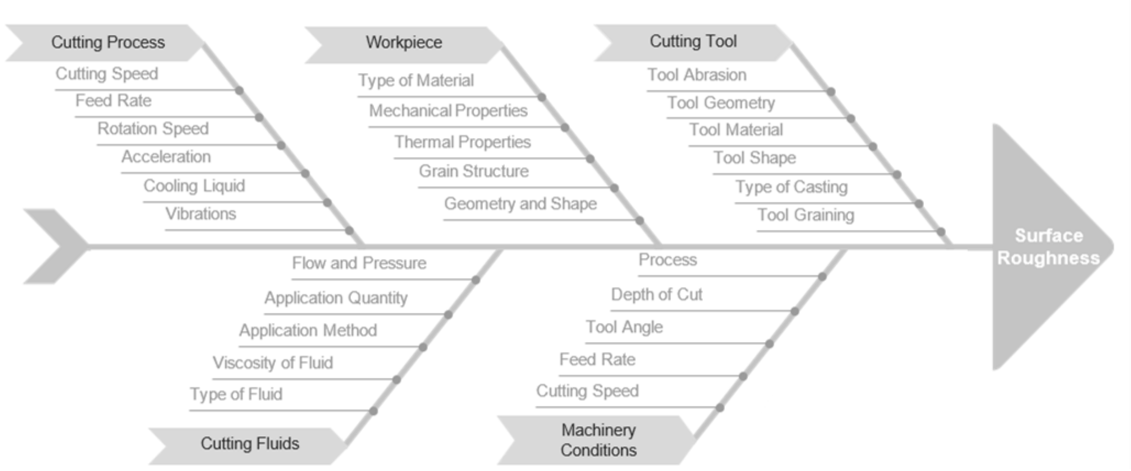

Figure 3: Revised Fishbone diagram for Surface Roughness Parameters.

the reasons for the poor machinability of austenitic stainless steel.

4. Discussion

The application possibilities and benefits of austenitic stainless steels are increasing in various fields of production due to their properties, high ductility, high durability, and excellent corrosion resistance. Although it is a widely used material, users have often reported machining difficulties encountered during machining.

Fishbone diagram in Figure 3 summarizes the results of studies and experiments focused on machining stainless steel [20-21, 24, 32-33]. It presents a synthesis of known results that point out the most important factors that need to be addressed when machining these steels. In terms of machining these steels, it is essential to deal not only with the quality of the machining itself but also with the cost efficiency associated with machining the steels. From this perspective, the lifespan of machining tools is a significant attribute.

Many process variables are involved during the machining process. Under such circumstances, it is difficult to standardize the machinability of steels. Working conditions can be very different in an industrial scenario. Considering the technological and industrial validity required by the research work, it is worthwhile to determine the maximum performance conditions in the machining of austenitic stainless steels. Optimization of machining variables can be developed using fuzzy logic, genetic algorithm, Taguchi method, RSM, neural networks, etc. These are included in studies of maximum tool life, minimum cost, best surface finish and dimensional accuracy. The effect of tool coatings is also important to study, as multi-coated tools significantly improve the machinability of these steels. It was also found that discussion of the behavior of austenitic stainless steels during high-speed machining is rare.

5. Conclusion

Various experimental studies on the parameters for machining stainless steel were mentioned in the article. The presented paper has reviewed, that austenitic stainless steels are used more than any other grades and that these are considered a difficult material to machine. Literature review showed that most of the research work is carried out on 300 series austenitic stainless steels. Researchers have focused on the effect of depth of cut, feed rate and cutting speed on various parameters like surface roughness, tool wear, for hard, ductile materials like stainless steel Increasing the cutting speed will cause a dramatic reduction in tool life. Feed variation at high cutting speeds has a little effect on tool life. The surface treatment directly depends on the machining conditions. A good finish can be achieved with minimum depth of cut, maximum spindle speed, and low cutting speed.

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