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Selected aspects of the design of special monolithic carbide milling cutters for austenitic steels

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Abstract

In many machining applications, the appropriate selection of cutting tools in relation to the type of material being machined, the machining parameters and the required shape and dimensional accuracy is of particular importance. This especially applies to operations requiring the use of specific tools, i.e. tools that are not included in the standard offer but are tailor-made according to the individual needs of the customer. The article focuses on the machining problems of selected austenitic grades of stainless steel and the selection of technologies (i.e. machining parameters and strategies and tool geometry) concerning the design and use of special monolithic carbide milling cutters. The possibilities of manufacturing elements from austenitic steels with high shape and dimensional accuracy and high surface layer quality are limited. Due to their high ductility, the tendency to create growths on the cutting edge and the high compression strength coefficient, these materials pose a serious technological challenge. The analysis of phenomena presented in the article forms the basis for developing guidelines for designing the machining process using special monolithic carbide cutters dedicated for specific applications.

Keywords: Austenitic Stainless Steel, Milling, Tungsten Carbide Tools, Speciall Shape Cutting Tools, End mill stabillyty/durability

1. Introduction

Stainless steels are a widely used group of steels due to their physical properties and, above all, their resistance to corrosion (Małek, 2022). The unique physicochemical properties of these steels are obtained by doping appropriate alloying elements, among which, chromium and nickel are the most important. There are four main types of stainless steels, namely austenitic steel, ferritic steel, martensitic steel and ferritic-austenitic steel (so-called duplex), of which the largest share (about 70% of the market) are austenitic stainless steels. The full potential of these steels resulting from physical and operational properties is commonly exploited, inter alia, in chemical, petrochemical, automotive, railway, shipbuilding, aviation and construction applications and in the production of household appliances and jewellery (Bagaber, 2018). The austenitic stainless steel grades that are the most popular and the most widely available on the market include steels of type 304 and 316L.

Machining stainless steels, including austenitic steels, presents a considerable challenge and technological problem for both manufacturing companies and manufacturers of cutting tools. Due to the physical properties of, for example, high ductility and low machinability, these materials pose a severe technological challenge during machining (Berkani, 2015), (Szczotkarz, 2020). Their processing is associated with the intensive wear of the cutting edge, which significantly affects the shaping process and the cost of production of products made of this type of material. The problems of austenitic steel processing particularly relate to obtaining the desired technological properties of the surface layer. Meeting the construction requirements in this respect requires selecting appropriate machining conditions, which includes the cutting process parameters, the type of coolant, the type of material and geometry of the tool and the selection of the protective coating. Ensuring the proper stability of the machining process is also related to the selection of the machine tool because machining stainless steel generally requires more power than carbon steel processing, and the fastening of the tool and the object must be very rigid.

Despite the continuous development of materials and protective coatings used for cutting tools, the machining of the selected type of stainless steel using the general geometry of the tool is inefficient (there is very rapid wear of the tool, which translates into process efficiency and the quality of the machined surface). An alternative strategy is to prepare a dedicated cutting edge geometry in relation to the specific workpiece material, tool material and protective coating used. This fits into the modern development trends of machining with special tools with a specific geometry, which are oriented towards producing elements with high shape-dimensional accuracy and high technical quality of the surface layer. These possibilities remain limited in the case of austenitic stainless steel processing, which is why the problem of the appropriate selection of tools (i.e. material, geometry and coating) as well as parameters and machining strategies is of particular importance. In addition, there is a demand on the market for products that meet individual customer requirements. A particular example are special tools with a dedicated cutting edge shape for a specific application (often referred to as so-called “shaped tools” in the production nomenclature). They are most often created for an individual technological need. Still, this is profitable in many cases due to significantly reducing the time and costs of manufacturing a given product.

A typical example of special-shaped tools are step drills, characterized by different working diameters and a strictly defined technological transition between these diameters. Step tools are most often made based on technical documentation under a specific construction feature(e.g. a hole of a certain size), and the possibility of using them in other applications is quite limited (Fig. 1 and Fig. 2). It is also worth emphasizing that the use and technology of special step tools intended for shaping holes are not demanding, and the selection of appropriate processing parameters does not pose a significant technological challenge.

Fig. 1. Examples of special tools manufactured by Poltra Sp. Z O.O. (own elaboration)

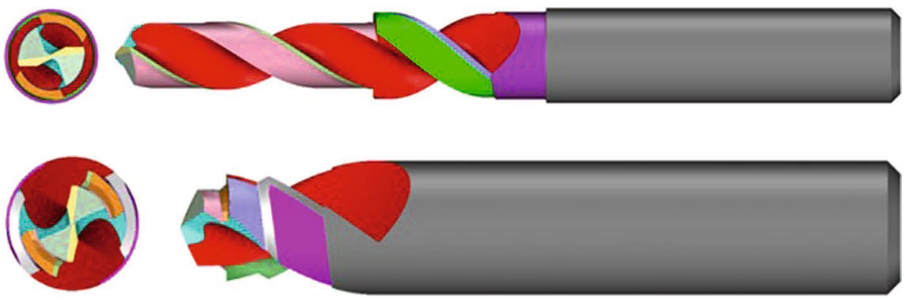

Fig. 2. Examples of shapes of step tools: with an angular transition (top) and with a transition according to the defined shape (bottom) (own elaboration)

The situation is different when it comes to designing special-shaped tools for typical milling operations. In this case, it is necessary to analyse the design features to obtain thorough shape and dimensional accuracy. Designing and manufacturing a cutting tool that enables proper and effective work is also necessary. In many cases, the use of special tools allows a significant further reduction of the workmanship time, especially in situations where a given construction feature occurs repeatedly. Such an example is discussed in the literature (Małek, 2022), where variants are presented, and the final concept

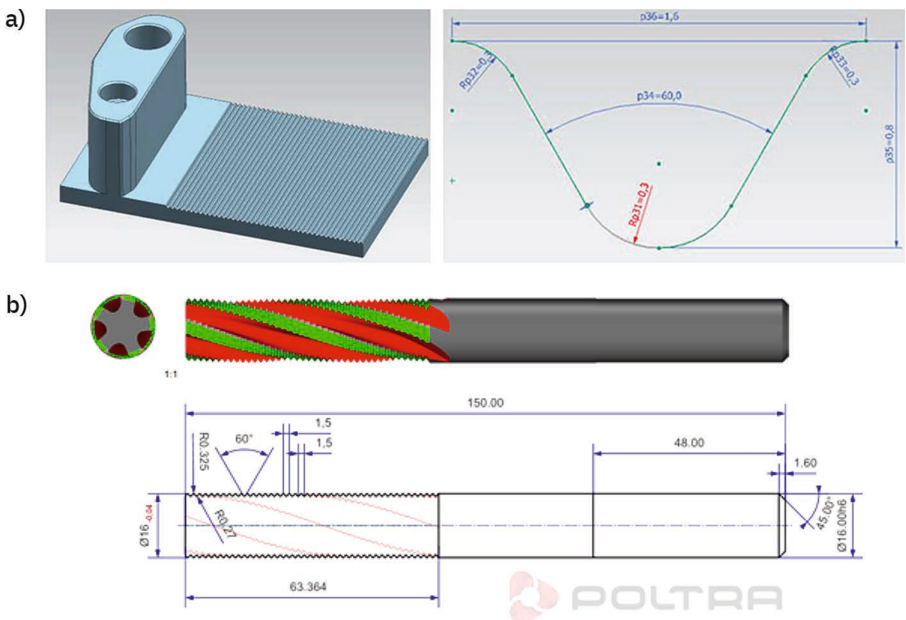

Fig. 3. An example of a component with the shape required for mapping (a) and a special tool designed to produce the required shape (b) (Małek, 2022)

of the special tool design is proposed (Fig. 3a and 3b). It has been shown that the use of a special tool with a complicated cutting edge geometry enables a significant reduction in machining time (forty-two times in the analysed case).

The aim of this article is to analyse the phenomena and problems occurring during the cutting of austenitic stainless steels. Stainless steels are a material group that varies in mechanical, chemical and machining properties, which is why it is often inappropriate to use one cutting edge geometry to process such a diverse material group. It is also worth noting that leading tool companies mainly focus on creating universal tool solutions with the widest possible use. As a result, we obtain a product (tool) that does not meet individual customer expectations, which in turn leads to the search for alternative solutions. The article will indicate the directions of work leading to improved machining efficiency, which is the basis for developing guidelines for designing the machining process using special and dedicated monolithic carbide cutters for specific applications.

2. Machinability of austenitic steels

Stainless steels do not constitute one strictly defined material in terms of chemical composition and mechanical properties. This group includes several families of separate alloys, which are distinguished by a characteristic microstructure (ferritic, martensitic, austenitic and austenitic-ferritic), chemical composition and to some extent, different physical properties. A common feature of these alloys is the chromium content (>11%), due to which these steels have high corrosion resistance (Elewa, 2021) (Tylek, 2014). This resistance is the main feature that results in such a wide use of stainless steels in industry.

During the machining of austenitic stainless steel, the phenomenon of compression reinforcement occurs, and in the state after cold plastic deformation, its strength increases, significantly affecting the wear rate of the cutting edge. Despite the strong compression reinforcement, the high ductility of this material causes the formation of long chips, which makes it difficult to drain them effectively from the machining zone. This results in built-up edge on the cutting edge and thus results in a significant increase in cutting forces. The increase in cutting forces also increases the load on the cutting edge. There is increased friction, which translates into an excessive increase in temperature in the cutting zone. It is worth noting that the thermal conductivity of stainless steels is about three times lower than carbon steel, which significantly hinders heat dissipation in the treatment zone. These factors negatively affect the cutting edge durability, and as a result, the cutting edge wears out faster.

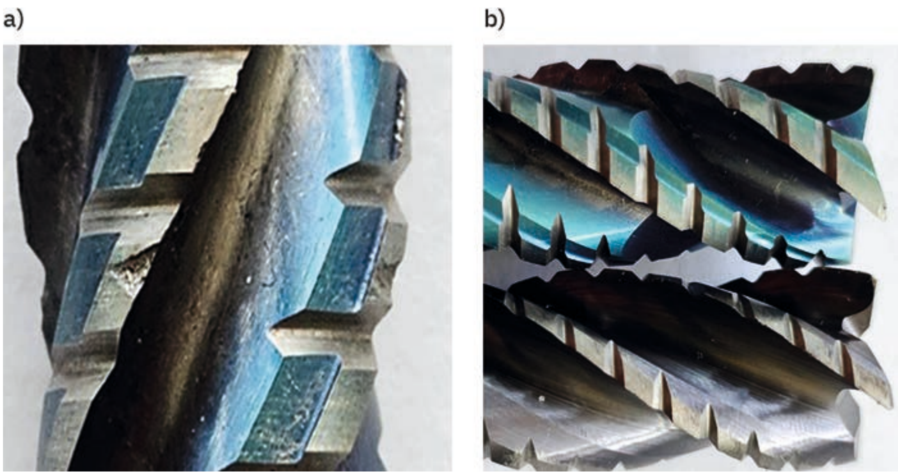

Fig. 4. Typical mechanisms of wear and damage of the tool during the machining of austenitic stainless steels: (a) chipping of the cutting edge during rough machining as a result of contact of the edge with the reinforced material of the flash created at the edge of machining material; (b) catastrophic damage to the tool coating: above – a three-layer sandwich coating, below the TiAlN coating (own elaboration)

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Figure 4 shows exemple mechanisms of tool wear during austenitic stainless steel machining. Dedicated carbide tools were used for processing. As the presented examples show, even a slight wear of the cutting edge leads to the rapid and, consequently, catastrophic wear of the tool. The main reasons for such rapid wear are the physical properties of stainless steels, inadequate tool geometry (e.g. inadequate choice of cutting edge angle) or poorly selected machining parameters

In terms of the selection of stainless steel machining technology, it is worth emphasising the large diversity of mechanical, chemical and machining properties in the group of these materials. The selection of tool geometry and machining parameters is therefore a difficult issue and in many cases requires an individual approach because the use of the same tool geometry in such cases is inappropriate. The general good practices indicated in the literature regarding austenitic stainless steel machining technologies include several highlighted in the literature (Elewa, 2021) (Odedeyi, Abou-El-Hossein & Liman, 2017) (Muthuswamy, 2022):

- collecting larger machining allowances than in the case of structural steel, which is mainly associated with the elimination of the adverse impact of compression reinforcement (machining with small allowances often results in rapid abrasive wear of the cutting edge due to increased friction of the cutting edge with the reinforced material);
- the use of effective cooling of the machining zone, which translates into lowering the temperature in the cutting zone, reducing the adhesion of the material to the cutting edge and improving the efficiency of discharging the machined material from the cutting zone;
- use of a suitable tool coating to reduce friction (reducing the temperature rise in the cutting zone);
- ensuring high rigidity of the MGFT (machine tool-grip-fixture-tool) system.

In the cutting process, the accuracy with which the tools will be made and the tool material selection significantly impact the shape and dimensional accuracy, machining efficiency and ultimately, the cost of manufacturing. Sintered carbide is a commonly used tool material that, to a very large extent, meets the requirements for cutting tools, i.e. high wear resistance, high hardness, resistance to changes in machining properties as a result of working at elevated temperatures and chemical inertness in relation to the workpiece. In their structure, carbides of hard-fusible materials mainly have tungsten as well as titanium or molybdenum, which give this material the desired characteristics that a cutting tool should have. Sintered carbides are relatively easy to form and precisely shape – they can be produced in different shapes and sizes, which allows for adapting the tools to specific applications. As a material, sintered carbide is also very well treated with grinding and lapping, which enables the precise shaping of the geometry of the cutting edge. All these features make carbides an irreplaceable tool material used in the machine industry, where the main emphasis is on machining efficiency, the durability of the cutting cutting edge and workmanship accuracy.

3. Technology of special monolithic carbide milling cutters

3.1. Design and processing

Carbide cutters are produced using specialised multi-axis tool grinders adapted for grinding sintered carbide (Fig. 2). The grinding process itself is performed using grinding wheels made of synthetic diamond on a resin, metallic or hybrid matrix (Fig. 3). In order to make the tool, it is necessary to prepare a machining program using dedicated software. An example of such a program is NumRoto (Numroto, 2023). Based on geometric guidelines such as working length, diameter, rake angle, application and inclination angle of the main cutting edge, a visual design of the tool is created (example in Fig. 7), which is sent to the machine control system to first verify its correctness and to then make the product. This process yields a product resulting from grinding, which is then subjected to analysis of the workmanship in terms of quality and geometry. After confirming the correctness of the product, it is subjected to further operations determined by their specified purpose. Such additional operations may include polishing or drag-finishing the cutting edge , cleaning and applying a protective coating.

Fig. 5. Saacke 5-axis grinder with chain feed system for semi-finished products (own elaboration)

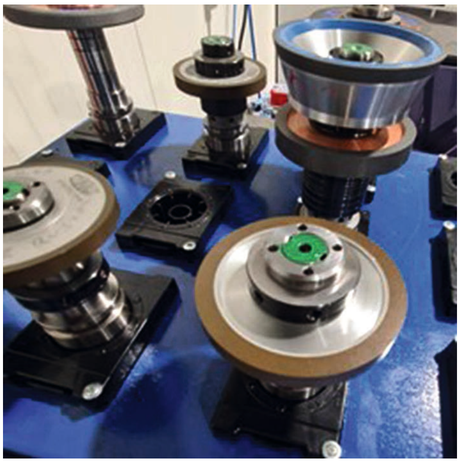

Fig. 6. Examples of diamond grinding wheels used in the manufacture of solid carbide cutting tools (own elaboration)

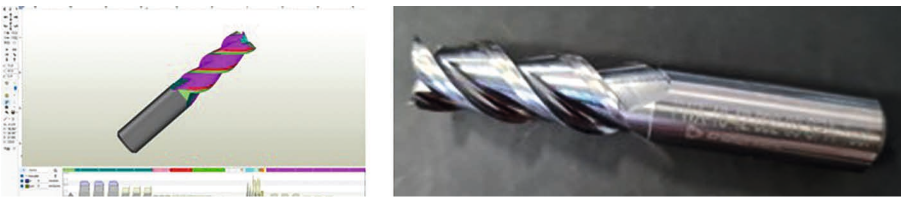

Fig. 7. (a) The design of the tool in NumRoto and its visualisation with the colour marking of individual operations; (b) an example of a tool created on the basis of a defined processing program (own elaboration)

3.2. Rounding of the cutting edges of the carbide tools

The analysis of the literature (Cichosz P. K., 2018) (Li, 2022) (Bakar, 2020) and the authors' own research indicate that the quality of the cutting edge very much influences the durability of tools. During grinding of carbide cutters, especially during operations related to shaping the chip groove, microchipping of the material on the cutting edge occurs, negatively affecting the operational properties of the tool. This can be improved by applying a rounding of the cutting edge by rounding in smoothing or polishing operations (Cichosz P. K., 2018). As a result, the roughness of the working surfaces of the cutting edge is reduced (which reduces friction in the cutting zone), the number of chips on the edge is reduced (which reduces abrasive and adhesive wear). The rounding of the cutting edge positively affects the adhesion of the coating and its splinter resistance during impact treatment.

Different sizes of micro-roundings of the cutting edge are used depending on the material being processed. For tools dedicated to processing stainless steel, the most common value of the micro-radius of edge rounding is within the range of 3-8 μm. This type of cutting edge preparation increases the durability of the cutting edge several times (Cichosz P., 2006). However, it should be remembered that there is a simultaneous increase in cutting forces.

Below, Figs. 8 and 9 show a comparison of the cutting edge obtained directly in the grinding process and subjected to controlled rounding. Edge measurement and analysis were performed using the Alicona Infinite Focus SL microscope.

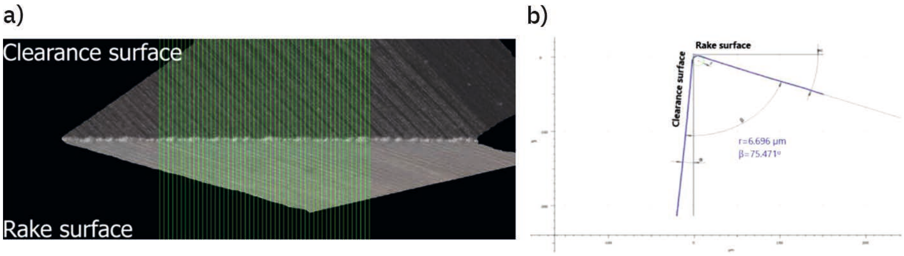

Fig. 8. View (a) and results of the analysis of the average radius of rounding of the cutting edge (b) immediately after making the tool – visible micro chips of the cutting edge (radius of rounding 6.7 μm) (own elaboration)

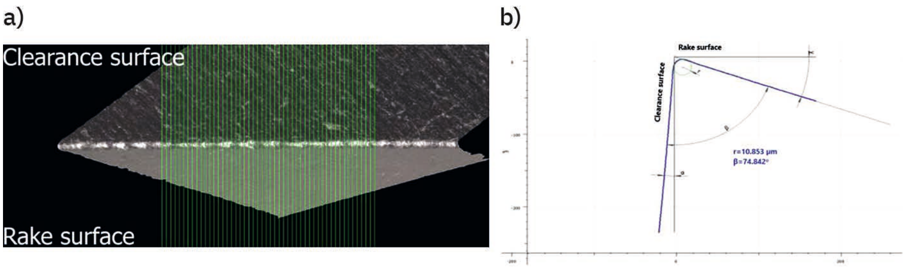

Fig. 9. View (a) and results of the analysis of the average radius of rounding of the cutting edge after a controlled rounding process (10.86 μm rounding radius) (own elaboration)

3.3. Manufacture of protective coatings

The use of protective coatings on carbide-cutting tools significantly affects their durability and increases the area of practical application in machining processes. Using an appropriate protective coating with a strictly defined chemical composition reduces friction, improves chip evacuation efficiency and protects the cutting edge against the negative impact of high temperature in the cutting zone, especially when milling materials with low thermal conductivity or high ductility. Currently, most protective coatings are produced by physical vapour deposition (PVD) or chemical vapour deposition (CVD) processes. With the development of materials engineering, the possibilities of using various types of tool coatings have significantly increased, from single-layer monolithic, composite or gradient coatings to multi-layer coatings applied on a nanometric, micrometric or superstructures scale.

In order to increase the processing efficiency, the appropriate selection of the type of coating used is crucial, particularly with regard to the material and type of treatment. Improper selection of the chemical composition means that the elements included in the tool coating can react with the workpiece. The basic tool coatings mainly contain compounds of titanium, aluminium, chromium or zirconium and, depending on the technological process used, they obtain different levels of hardness, usually in the range of from 2000 to even 4000 HV and different thicknesses of the protective layer in the range of from 1 micrometre to even 6 or 8 micrometres. Due to the use of a suitable composition, machining is possible, during which, the temperature in the machining zone ranges from 500 to 800°C. The process of preparing the tool for applying the coating is equally important. In order to improve the adhesion of the coating to the surface of the tool, thorough cleaning and drying of tools of any remnants of grinding and transport processes should be conducted. Also worth noting is the method of preparing the active surfaces of the tool in order to eliminate any contamination and surface discontinuities that, after applying the coating, may tend to generate stresses or damage to the surface of the coating.

4. Impact of cutting edge geometry on rate of wear

One of the main problems occurring during the austenitic steel cutting process is the very intensive wear of the cutting tool. As indicated in the literature (Cichosz P. K., 2018) (Li, 2022) (Denkena, 2011), the operation process of the cutting tool can be extended even several times by rounding the cutting edge. The rounding process takes place in special devices that not only shape the edge of the cutting edge, but also positively affect the process of finishing the tool's working surfaces (in the analysed case, the cutter). As a result, we obtain a reduction in the roughness of the working surface of the tool, which directly translates into a reduction in friction at the point of contact of the workpiece with the tool. The lower surface roughness of the cutting edge also results in a better adhesion of the protective coating. In addition, the rounding of the cutting edge reduces its damage (chips), which additionally increases the resistance of the edges to abrasive and adhesive wear. The benefits of rounding cutting edges are very important for the operation of the tool, so this process should be thoroughly examined, analysed and introduced as a required step in the process of manufacturing carbide-cutting tools.

As part of the authors' own research, an analysis of the impact of the geometry of the cutting edge on the efficiency of milling austenitic steel STT17/13SW was conducted. The tests were performed for two prototype cutters with a diameter of 10 mm (Fig. 10) assuming an rake angle as a variable parameter – 8 degrees for one prototype and 12 degrees for the other. Each tool was used to mill 10 grooves to a depth of 5 mm in a 140 × 55 × 30 mm sample. The grooves were made in a single pass using the following cutting parameters: n = 3350 rpm, V_f = 200 mm/min, a_p = 5 mm, total cutting path = 550 mm. The tests were the basis for determining the degree of tool wear and analysing changes in the roughness and depth of the grooves along with the cutting

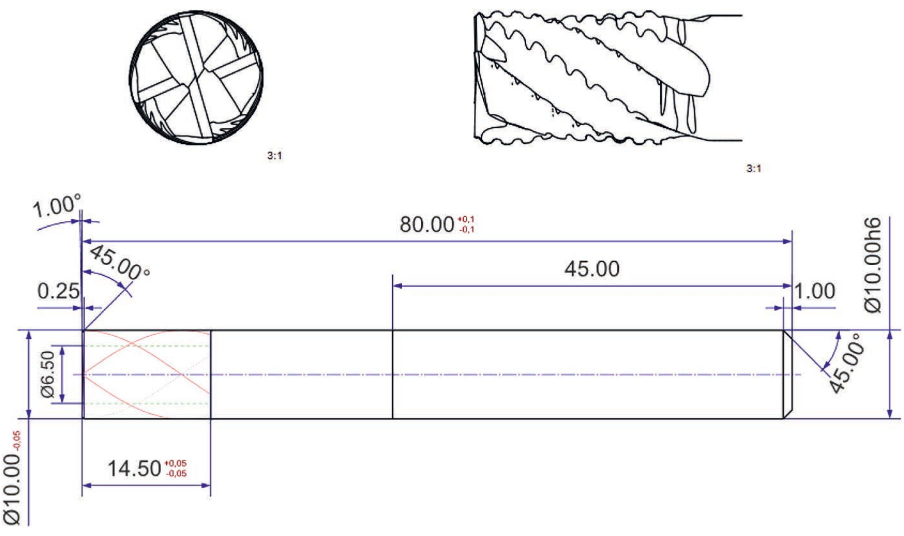

Fig. 10. Geometric details of the tool prototype (own elaboration)

path. The measurement of the tool after processing was performed at a distance of 4 mm from the face surface for each of the four cutting edges. For each groove made, the roughness Ra and the depth were also measured, taking into account the value created on the left and right edges of the groove of the flash created at the edge of machining material.

On the basis of the conducted research of the austenitic steel rough milling process (Fig. 11), a negative impact of increasing the rake angle on the edge strength of the cutting edge was found. Analysing the presented data, we can see that the average rounding of the cutting edges is 63% higher for cutting edge with a higher rake angle, 12° in this case. In order to improve the durability of the cutting edge, smaller rake angle should be used. For the rough machining of austenitic stainless steels, the durability of the cutting edge is one of the main problems in achieving stable and efficient machining.

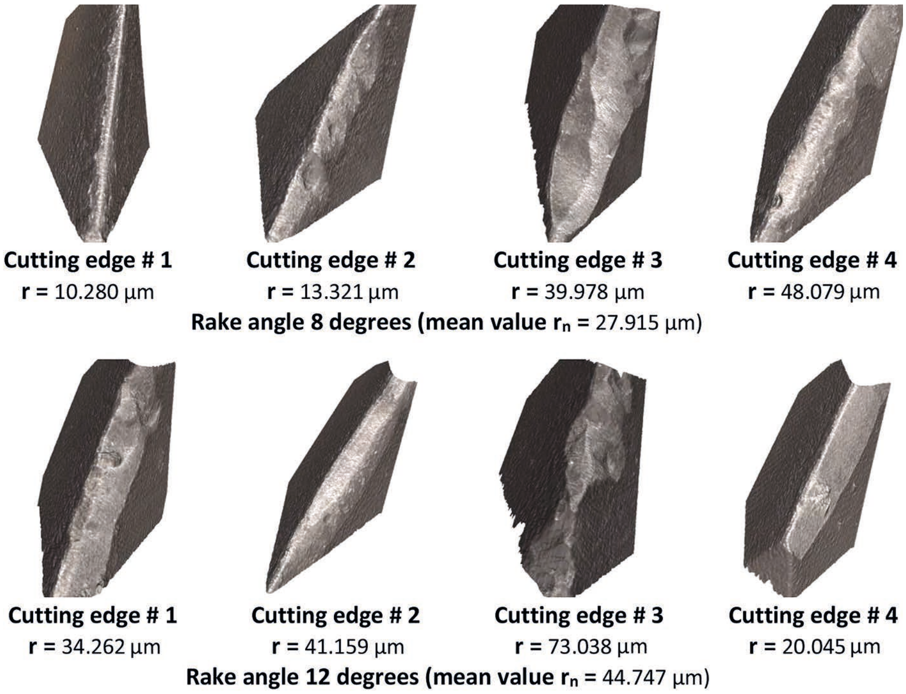

Fig. 11. Visualisation of cutting edges after milling, cutting path 500 mm; r_n – radius of rounding of the cutting edge (own elaboration)

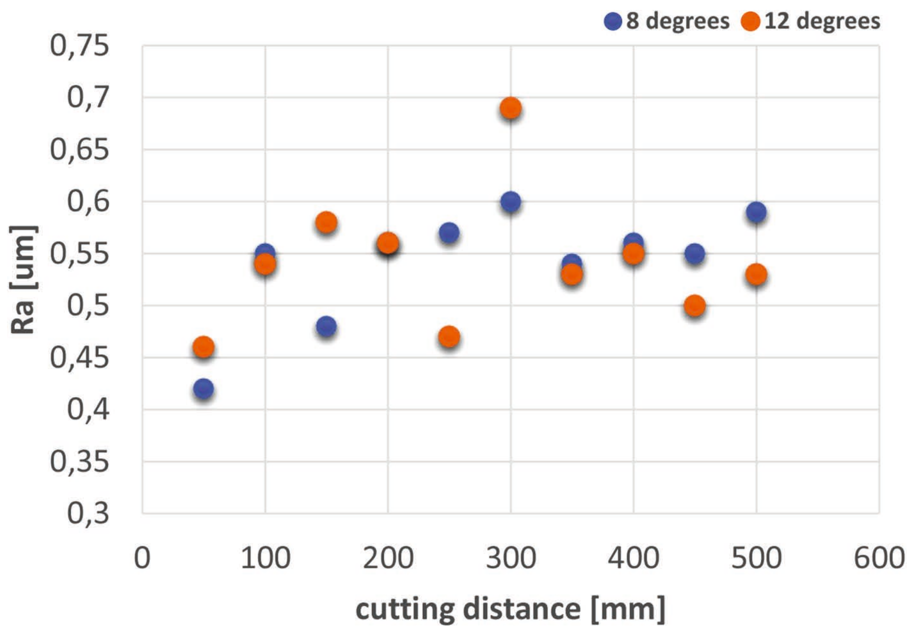

Fig. 12. Change in the roughness of the groove surface along with the cutting path for the two tested rake angle of 8 and 12 degrees (own elaboration)

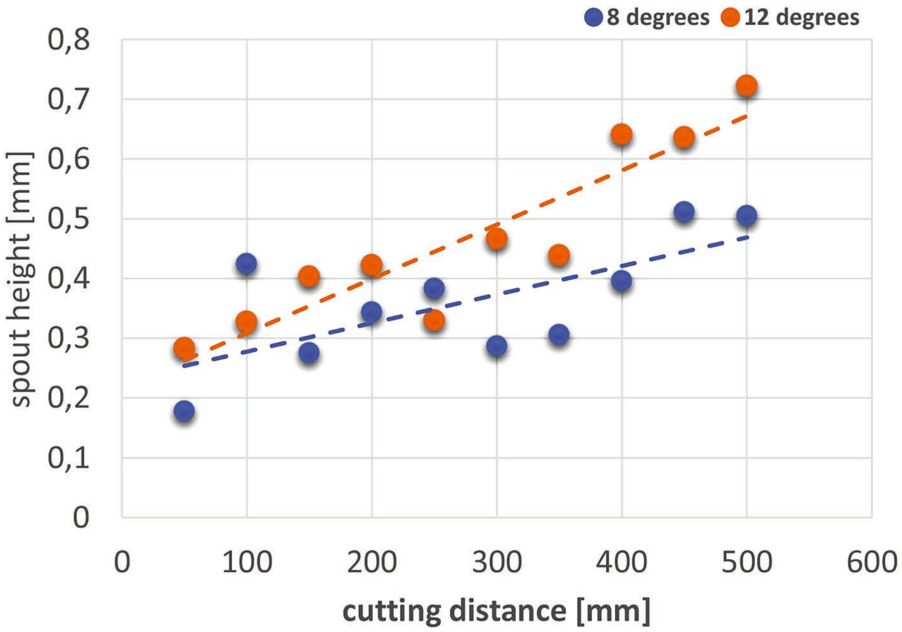

Fig. 13. Changing the height of the flash along with the cutting path for the two tested rake angle of 8 and 12 degrees (own elaboration)

An increased rake angle also increases the height of the flash created at the edge of machining material – Fig. 13), which can also be related to previous observations, which show that a larger rake angle causes faster wear of the cutting tool, directly translating into the height of the flash. Surface roughness for the analysed rake angle erquires further testing because, for the parameters that were used during machining (rough machining), this roughness reaches large values ranging from 0.4 to 0.7 μm. As shown in Fig. 12, after a certain period of operation of the tool (cutting path 300 mm), the surface roughness for the two tested geometries stabilises, while we can notice that for the 12° rake angle, the roughness reaches lower values. The lower roughness is related to the previously described process of rounding cutting edges (Fig. 11), which translates into better surface quality.

5. Conclusions

Considering the properties of stainless steels, undertaking work aimed at determining the most effective working conditions of cutting tools, both standard in the means of general availability and tools with special application specifics seems to be obvious. For this purpose, a thorough analysis of the tool material in terms of its durability and use in difficult-to-machine materials is necessary. Another aspect is the appropriate selection of the microgeometry of the cutting edge and protective coatings aimed at increasing the durability and improving the quality of products produced by subtractive manufacturing . Finally, after determining the physical basis of the SA treatment process, special attention should be paid to the possibility of eliminating or minimizing the adverse impact of phenomena occurring during the subtractive manufacturing treatment of this type of structural material. The following points are found to be important:

- high compression strength coefficient,
- low thermal conductivity,

tendency for long chip formation exists due to the high ductility of austenitic steels. Detailed analysis of these phenomena enables the determination of the most effective machining parameters from the point of view of machining and from the point of view of tool durability, the production of products with improved operational properties.

Further work in the field of austenitic steel processing and dedicated cutting tools intended for this type of materials will include the analysis of

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phenomena occurring in machining processes. This is due to the need to design the tool in such a way that for different diameters, in relation to the shape of the tool itself, appropriate values of the cutting edge load are obtained. This has a special impact when the tool works simultaneously with many different diameters. This affects the cutting parameters of such a tool by assuming the geometry constancy of the cutting edge along the working length of the tool. The cutting edge operates at different cutting speeds, which may result in the earlier wear of certain tool elements. In this case, a thorough analysis of the case and the possibility of using the most effective parameters and working conditions are important.

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