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# A Short Literature Review on Turning and Milling of Cobalt Alloys

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## Abstract

Among the existing machining processes, turning and milling are characterized as the most used and consequently are considered the most important. Machining moves a market estimated at around 10% of gross national production. Many industrial components and parts are subjected to severe operating conditions, in corrosive environments, high temperatures what causes wear. With the development of industries, there is a need for steel alloys with different properties, to meet different purposes. Cobalt alloys, as well as others, arose from the need to develop metals that would meet the growing demand in applications with high temperatures and high working stress in gas turbine components. Due to their high mechanical and thermal resistance, these alloys are difficult to machining, a situation that requires in-depth studies to reduce process costs and improve the surface quality of machined parts. Machined surfaces may have different textures depending on the process. Turning and milling generate grooved profiles due to tool/part interaction. In many cases, roughness is used as an output parameter to control the process. Another important factor is the wear of cutting tools, which must be selected according to the material properties of the workpiece, machine tool and other parameters that influence its wear. Controlling the useful life of the tool is a decisive factor when you want to avoid loss of productivity, with fewer stops for changes, consequently, you have a more effective and economical production. The present study presents a brief review of the literature regarding turning and milling of cobalt alloys, regarding the optimization of machining parameters, tools used and the use of lubri-cooling techniques, with the objective of reducing the roughness of the parts, the tool wear, improve surface integrity and contribute to the sustainability of manufacturing processes when machining difficult-to-cut materials. In this review, a comparative analysis of the results is presented, indicating the gaps in research such as classification and processing of alloys, formation of carbides with non-uniform distribution, which impairs the performance of the tools. Some suggestions for future work indicate the absence of studies on the use of diamond and CBN tools, clarify the interaction medium lubricant-coolant-coating of the tools-alloy chemical composition and cutting parameters, in addition to dynamic analyzes in the cutting of hardened materials.

**Keywords:** Literature review, turning, milling, cobalt alloys, surface integrity

## 1. Introduction

In highly developed industrialized countries, machining moves a market estimated at around 10% of gross national production. About 70% of the machines operating in the industry are formed by machine tools related to machining (Youssef, 2016).

Many industrial components and parts are subjected to severe operating conditions, in corrosive environments, high temperatures and end up suffering wear. An example of these conditions are hot dip galvanizing roller bushings, which need surface protection to reduce costs for component replacement or corrective maintenance (Scheid, 2007).

Elwood P. Haynes developed in his laboratory a series of cobalt-based metal alloys to produce various critical parts of internal combustion engines that he called "*stellites*" in the 1900s. Haynes derived this name from the Latin word “Stella” which means “Star” due to its star-like brightness. Initially, Haynes developed a nickel-chromium alloy (Ni-Cr) and a cobalt-chromium alloy (Co-Cr) and obtained these two superalloys patented in 1907. After his subsequent research, Haynes produced two new groups of alloys based on cobalt with the addition of tungsten (W) and molybdenum (Mo). He added these two new alloys under the group name "*Stellites*", and they were patented in 1912. Haynes received another patent in 1913 for the development of another cobalt-chromium-molybdenum-tungsten-carbon complex superalloy (Co-Cr-Mo- WC) known as Haynes alloy 6B (Hasan et al., 2016).

Cobalt alloys, like other alloys, arose from the need to develop metals that could meet the growing demand in applications with high temperatures and high working stresses in gas turbine components. Around the year 1900, patents were issued for alloys containing the Co-Cr and Co-Cr-W systems, such as the U.S. 873,745, being the basis for most cobalt superalloys. These materials were developed for applications in aggressive media and wear-resistant surfaces. The hardness of these alloys is very high compared to other metals and metallic alloys; they have high wear resistance, corrosion resistance and the ability to maintain these extraordinary properties at extreme temperatures for long periods of time (Bohatch & Scheid, 2014).

Hard turning is the dominant machining operation performed on hardened materials. It consists of the single point cutting process of parts that have hardness values above 45 HRC but are more typically in the 58 - 68 HRC range. Sandvik Coromant defines hard materials as those with hardness above 42 HRC up to 65 HRC. Hard milling (HM) definitions vary by company and application. A conventional way of defining considers materials with hardness between 45 - 64 HRC (Davim, 2008).

Machined surfaces can have different textures depending on the process. While milling and grinding induce a grooved profile, polishing generates a more regular surface profile. Sometimes a shot peening is applied to the surface to produce a gutter profile that improves corrosion resistance (Jebaraj et al., 2017). Despite the benefits of coatings, turning and milling processes generate grooved profiles due to tool/workpiece interaction; if not controlled, these profiles can be dangerous, especially in highly corrosive environments (Oliveira et al., 2020). For this reason, the quality of the machined part is typically defined in terms of its roughness (Jebaraj et al., 2017; Policena et al., 2018).

In many cases, roughness is used as an output parameter to control a machining process. It depends on various input parameters such as machine tool, tool geometry and material, workpiece material properties, and machining operation. Thus, the quality of the machined surface finish can help to measure productivity and machining performance (Machado et al., 2009).

Another important factor in the machining process is the wear of the cutting tools. These must be selected according to the material properties of the workpiece, machine tool and other parameters that influence its wear. The longer tool life also means less downtime for changeovers, hence more effective and cost-effective production. Controlling this factor is decisive when you want to avoid loss in productivity (Camana, 2019).

From the mentioned factors, studies are necessary in the machining of these alloys, seeking to find the ideal values for the parameters used to increase the useful life of the cutting tools, reduce the roughness and the costs of the process. Elements such as nickel and chromium combined with cobalt make machining this material a challenge, as they increase hardness and reduce ductility, making machining difficult and causing premature wear of cutting tools, in addition to impairing their surface finish. The present paper made a brief review of the literature regarding turning and milling of cobalt alloys. The listed studies comprise aspects of tool wear and part roughness. The investigation contemplates the cutting parameters used, the lubrication and cooling conditions and the cutting tools.

## 2. Literature Review

In this topic, cobalt alloys, surface integrity in difficult-to-cut materials and works that presented different machining techniques in turning and milling of these superalloys are characterized.

### *2.1 Characterization of Cobalt Alloys*

In industry, many components are subjected to critical and highly aggressive conditions, which cause erosive wear of parts. One possibility to improve their service life is to wrap them with a surface layer or build the support with cobalt alloys (Bohatch & Scheid, 2014; Yingfei et al., 2017).

Cobalt-based alloys are widely used where hot corrosion is a major problem or in structures subjected to high stresses and temperatures (Geddes et al., 2010). They are used to increase the useful life of equipment in various industries, such as petrochemical, automotive, galvanizing, among others (Bohatch & Scheid, 2014).

Among the main characteristics that make this type of alloy applied in industry are higher melting temperature than other alloys, high resistance to thermal fatigue, good weldability, and resistance to hot corrosion (Geddes et al., 2010; Yingfei et al., 2017).

*Tribaloy* family cobalt-based alloys (T-400®, T-800®, T-900, T-401 and T-700) were developed by DuPont® in the 1960s and are mainly characterized by high wear resistance at high temperatures. These characteristics are mainly produced by the precipitation of intermetallic phases, called *laves*, in a softer eutectic matrix (Blau et al., 2009; Scheid, 2007; Tavakoli et al., 2008). The chemical composition and hardness of some cobalt alloys are described in Table 1.

Table 1. Chemical composition of cobalt alloys (ASM Handbook, 2004; Stellite, 2021; Haynes, 2021).

| Element (% wt.) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Alloy | Co | Cr | W | Mo | C | Si | Fe | Ni | Mn | Hardness (HRC) |
| *Tribaloy* T400 | Bal. | 9 | - | 28 | - | 2.6 | - | - | - | 52 |
| *Tribaloy* T800 | Bal. | 18 | - | 28 | - | 3.9 | - | - | - | 58 |
| *Stellite* 6 | Bal. | 29 | 4.5 | 1.5 | 1.2 | 1.5 | 3.0 max. | 3 | 1 | 42 |
| *Stellite* 12 | Bal. | 30 | 8.3 | - | 1.4 | 0.7 | 3.0 min. | 1.5 | 2.5 | 48 |
| *Haynes* 25 (L605) | Bal. | 20 | 15 | - | 0.1 | 0.4 | 3 | 10 | 1.5 | 21 |
| FSX 414 | 52.5 | 29 | 7.5 | - | 0.25 | - | 1.0 | 10 | - | 30 |
| ASTM F1537 | Bal. | 26-30 | - | 5-7 | 0.14 | 1.0 | 0.75 | 1.0 | 1.0 | 40 |

The *laves* phases are formed by molybdenum and silicon added in proportions greater than the solubility limit and provide wear and corrosion resistance when operating at high temperatures or under non-lubrication conditions, Figure 1. While the eutectic solid solution provides high ductility and fracture resistance. To avoid the formation of carbides, the carbon content is kept low. *Laves* phases have better stability at high temperatures compared to carbide-hardened phases. The amount of *laves* phases is usually between 35 and 70% of the volume and must be controlled, as it defines the properties of the material (Blau et al., 2009; Scheid, 2007; Tavakoli et al., 2008).

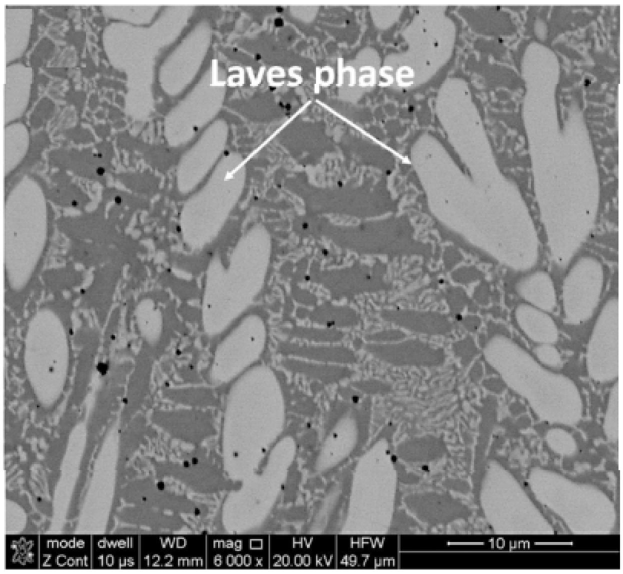

Figure 1. Microstructure of *Tribaloy* T-800 obtained by Scanning Electron Microscope (SEM) (Durejko et al., 2019).

### *2.2 Surface Integrity in Hard-to-Cut Materials*

Determining the functional parameters of the generated surfaces is the dominant paradigm shift in environmentally friendly machining. Texture can be described by the set of 3D features of a surface area

(Krolczyk et al., 2018). Integrity characterizes the quality of machined surfaces, interpreted according to the elements that describe the surface and subsurface structure of the material. It is generally defined by the chemical, metallurgical and topological properties of the surfaces, such as roughness, microstructure, microhardness variations and changes in residual stresses (Bordinassi et al., 2006).

The surface texture can be related to the performance of the component in your application. The finish of a machined surface consists of the union of several factors, normally divided according to the distance between the irregularities. The main ones are roughness, undulations, and shape errors. Each part can have a specific surface finish. Several factors must be considered, for example, the degree of coupling, coefficient of friction, appearance, and cost (Santos & Sales, 2007). Waviness and shape errors are manufacturing defects, so they should be avoided (Machado et al., 2009).

Roughness consists of fine irregularities resulting from the action inherent to the cutting process, such as built-up cutting edge, feed marks or tool wear. It is a surface change and is often used as a process output parameter. It depends on several parameters, such as machine tool, tool material and geometry, workpiece material or machining operation (Corrêa, 2019; Machado et al., 2009). Average roughness ($R_a$) is the most common parameter, easy to obtain and widely used in process control (Machado et al., 2009).

High contact temperatures at tool-chip and tool-workpiece interfaces promote tool wear by diffusion and oxidation in traditional machining processes. High contact pressures at these interfaces and sliding surfaces increase abrasive and adhesion wear. Catastrophic tool failure occurs when repeated loading and unloading causes cyclic stresses, which induce surface or subsurface failure and material loss (Astakhov, 2006). Tool life is essential in traditional machining, as considerable time is lost whenever a tool is replaced and reset (Davim, 2008).

The subsurface is as vital as the surface texture. Specifically, the microstructure and the state of residual stress are strategic parameters because the fabrication process can induce dramatic changes in the subsurface (Davim, 2008). The reduction of friction between the tool and the workpiece influences the reduction of deformation of the machined layer, which is a significant factor in determining microhardness (Paiva et al., 2017). The formation of sawtooth chips is one of the main characteristics in the machining of difficult-to-cut materials with defined geometry tools (Davim, 2008).

The state of the tool also greatly influences the surface quality of the part. Flank wear ($V_B$) modifies the geometric shape of the cutting edge, causing deterioration in the finish. Crater wear alters the curvature of the chip, facilitating flow and, consequently, improving the finish; however, an increase in this wear can cause tool breakage. Plastic deformation impairs chip control, impairing the finish. The cutting edge adhered to the tool can increase to a certain extent, breaking abruptly, or adhere to the part, damaging the finish (Almeida, 2010; Machado et al., 2009).

Machining without the use of fluids (dry) is quite usual, does not offer environmental risks and is more economical and reduces the harm related to the health of the operator. It is usually applied when cutting fluids would cause damage to machining, as in cases of using ceramic tools based on aluminum oxide (Machado et al., 2009). However, in some cases it is not possible to apply this machining method, mainly due to excessive tool wear and the consequent poor surface quality of the part, in addition to limiting machining to low cutting speeds, which reduces productivity (Shokrani et al., 2016).

There are some adversities in dry cutting processes, such as strong adhesion between the tool and the chip of certain materials in some situations. Several means have been developed in recent years (Figure 2) to control the temperature in the cutting zone and improve the overall effectiveness of the turning process, such as fluid coolant, high pressure coolants (HPC), internal tool coolant, lubrication minimum quantity (MQL), near dry machining (NDM), solid coolants/lubricants, cryogenic cooling, and use of compressed air/gases (Sharma et al., 2009).

The use of fluids can improve cutting conditions, surface finish of the part, reduce tool wear and machining forces and reduce machining costs. Fluid in abundance (wet or flood cooling) is the most used method, mainly motivated by its simplicity. It has good cooling action, but the lubrication is poor, because with low pressure, the liquid ends up not penetrating the chip-tool interface. It requires a large reservoir for the fluid, disposal is difficult for environmental reasons and there is a risk of operator intoxication (Tschätsch, 2008).

The minimum quantity lubricant (MQL) is a technique that has been gaining ground in the machining market. It consists of a very small rate of droplet lubricating-coolant applied as a mist over the cutting zone, along with compressed air. The advantages of this type of cutting are cost reduction, fluid disposal, machine cleaning, and the part is virtually dry after machining (Chetan et al., 2015).

Cryogenic machining is another more recent technique that consists of using liquid nitrogen (or liquid $CO_2$) at an approximate temperature of -200 °C which is injected into the cutting zone, causes a drastic reduction in temperature, and then evaporates directly. Due to the high cooling rate, the use of this fluid allows the application of high cutting speeds, and, in addition, the chips are severely cooled, becoming more fragile and breaking more easily, in addition to not having environmental damage (Youssef, 2016). In addition to the thermal advantages, this type of fluid acts to reduce tool wear due to abrasion and diffusion (Shokrani et al., 2016).

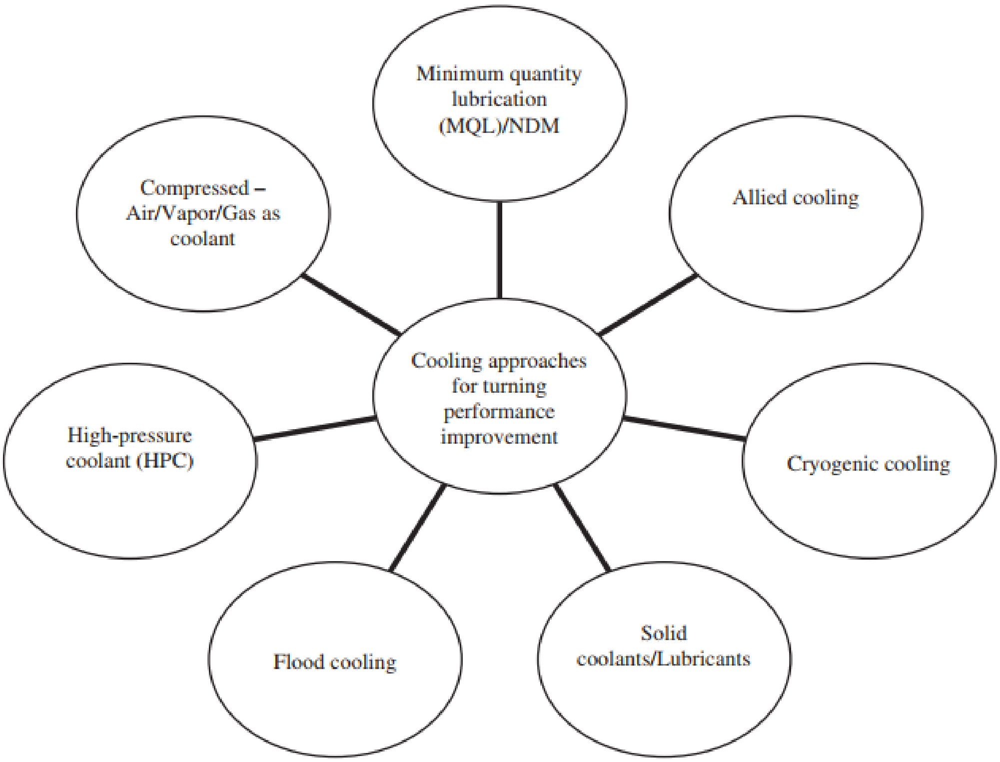

Figure 2. Techniques for reducing heat flux in turning (Sharma et al., 2009).

### *2.3 Machining Techniques in Cobalt Alloys*

Cobalt alloys are so hard and tenacious that they are difficult to machine, making the parts more expensive. Components are generally precision cast, so minimal machining is required. In most cases, machining is done by grinding instead of oblique cutting, which is another expensive operation (Hasan et al., 2016). This fact may be one of the reasons for the few works found in the literature. In the machining of cobalt alloys, there are works approaching various alloys in the turning and milling processes. In studies that relate turning:

Camana (2019) analyzed the *Tribaloy* T-800 cobalt alloy using $Al_2O_3$-based ceramic inserts to establish the economic machining conditions. For each pass, different cutting speeds were used, the tool flank wear was measured, and the machining time was timed. In the analysis from the economic point of view, graphs of the tool's life were generated, based on the end-of-life criterion, and expenses related to the process were analyzed. For equal and higher cutting speeds above 120 m/min, the tool was replaced early, as the end of life was reached, while speeds in the range of 90 to 110 m/min generated more uniform wear on the tool.

Shao et al. (2013), studied the cobalt alloy *Stellite* 12 using coated and uncoated cutting tools, varying the cutting parameters. The inserts used were uncoated tungsten carbide (hard metal) inserts (YT726 and YG610) and a TiAlN coated carbide insert (SNMG150612-SM1105). For each test, measurements were made on the flank wear of the tools, using an optical microscope. Among uncoated inserts, YG610 showed less wear than YT726 for all cutting conditions tested. In uncoated tools, the progression of flank wear generated tool breakage. At high cutting speeds, diffusion and chemical wear were dominant.

The *Haynes* 25 alloy is widely used in the aerospace industry, in parts for turbines and furnaces, among others. Andhare et al. (2021) sought to minimize the output variables by varying the input parameters, using method MQL and tungsten carbide inserts with zirconium coating (TNMG160406UF). Twenty combinations of values were tested for: cutting speed, feed, and depth of cut. *Minitab* 19 software was used to perform statistical analysis of variance (ANOVA) and identify the importance of each input parameter in the measured variables. With the help of the software, they defined the optimal values of the cutoff parameters for a multivariate analysis. Sarikaya and Güllü, (2015a) investigated the influence of cutting speed and coolant flow on mean roughness ($R_a$), using MQL coolant, using Taguchi methodology and using uncoated carbide tool. They tested three different types of lubricants: mineral oil, mineral oil with synthetic ester, and vegetable oil. They varied cutting speed and fluid flow, maintaining constant feed and depth of cut. The ideal combination for reducing tool wear and less roughness was with the use of vegetable-based cutting fluid, at maximum flow rate and minimum cutting speed. Sarikaya and Güllü (2015b) used carbide inserts (SNMG 120408-QM) without coating and varied the cutting parameters. The $R_a$ analysis for the combination of parameters was performed in the dry cut and flood cooling. The lowest values were obtained using medium cutting speed and minimum feed, with the use of coolant. With high cutting speeds, the roughness increased due to the progression of tool wear. Sarikaya et al., (2016) analyzed wear and roughness with three different lubrication-cooling methods: dry, flood cooling and MQL. They varied cutting speed and feed, with the same insert class as in previous research. The MQL lubrication-cooling method had better results than the others. For very high or very low cutting speeds, there was an increase in roughness and tool wear. In general, the lowest roughness values were observed with the lowest feeds. After optimization by the Taguchi method, the ideal combination to obtain the lowest roughness was the application of the MQL method, medium cutting speed, and low feed. To reduce wear on the tool the combination must be with MQL, minimum cutting speed and the highest feed. Finally, Sarıkaya et al., (2021) analyzed the performance of ceramic tools coated with *whiskers* in cutting the same alloy. They used dry cutting, plant-based fluid in MQL, nanofluid based on hBN (hBN-NMQL), nanofluid based on $MoS_2$ ($MoS_2$-NMQL) and nanofluid based on graphite in MQL (GR-NMQL). The cutting parameters varied. The observed output variables were thermal conductivity, viscosity, roughness, and tool wear. They concluded that the lowest roughness values can be obtained when using the minimum cutting parameters in the GR-NMQL system, followed by hBN-NMQL, BF-MQL and $MoS_2$-MQL. The main wear mechanisms on the tool were adhesion and abrasion, and the main types of wear were crater and notch.

In the ASTM F1537 alloy, Bordin et al. (2014) conducted a study on the influence of cutting speed and feed on surface integrity. They analyzed surface finish, subsurface microhardness, and residual stresses. They varied the cutting parameters and established three minutes as the cutting time. Figure 3 shows the main defects found, such as stains, burrs, adhered and torn off material, cracks, grooves and crushed carbides. They found that feed was the main factor influencing roughness, and that a smoother surface was obtained with the lowest feed. The lowest roughness was obtained with the highest cutting speed. Bogajo et al., (2020), measured roughness and cutting forces using cryogenics. The cooling system was designed based on thermal analysis of the heat flow in the machining process. The project was developed to optimize the geometry of the tool that contained a cavity to receive the cryogenic fluid ($N_2$). As a result, they found a 12% decrease in cutting forces compared to other cryogenic cooling methods, and 15% compared to dry cutting. Roughness values reduced by 12% compared to tests using the unmodified insert. With average cutting speeds, there was a 25% reduction in roughness values.

In machining the cobalt alloy *Stellite* 6, Ozturk (2014) used two different materials for cutting tools: ceramic reinforced with *whisker* and tungsten carbide. He varied the cutting speed and the feed, with the objective of defining the influence of the cutting parameters on the roughness. For each test, it measured the roughness and calculated the theoretical values from the Taguchi methodology. Ceramic tools performed better for the same cutting parameters. Feed was the parameter that most influenced roughness. Saidi et al. (2019) verified the influence of cutting parameters on the roughness of the part, cutting forces and material removal rate (MRR). They used a carbide tool coated by physical vapor deposition (PVD), with tip radii of 0.2 mm, 0.4 mm, and 0.8 mm for different combinations of cutting parameters. Based on initial measurements and with the aid of numerical methods, they defined mathematical functions that correlated the cutting parameters with the output variables. Valíček et al. (2019) analyzed the influence of cutting speed, feed, and depth of cut on the roughness of a part coated by the HVOF (high-velocity oxygen fuel) spray method. From various combinations of different cutting parameters and with the aid of computational methods, they defined a mathematical equation to predict roughness. In the mathematical model, the parameter that has the most influence is feed, followed by depth of cut and cutting speed.

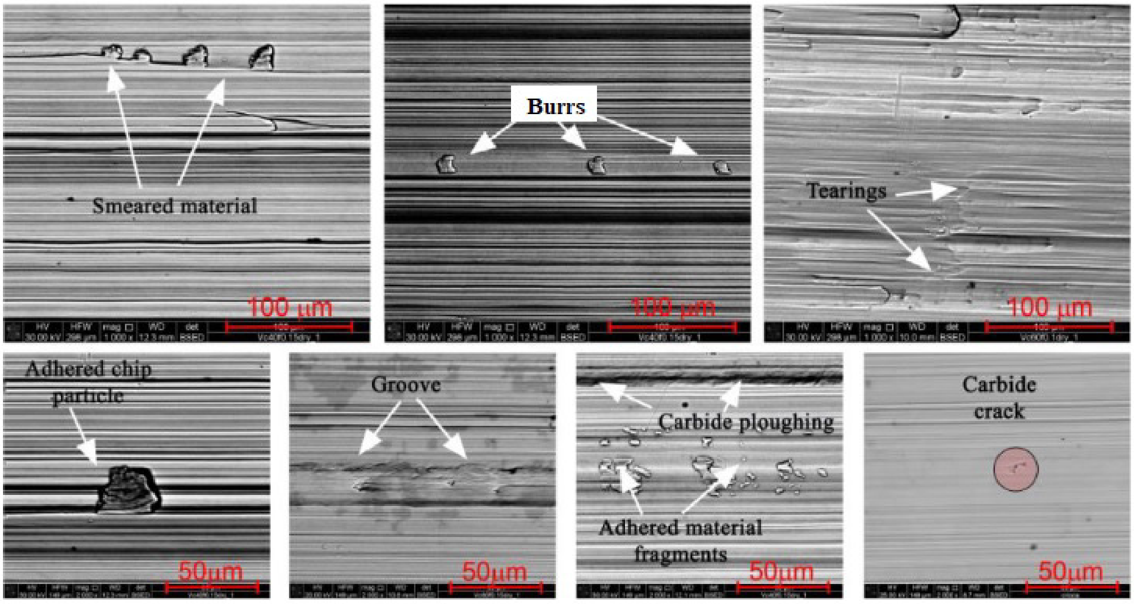

Figure 3. Image of surface machined in turning alloy ASTM F1537 (Bordin et al., 2014)

There are studies involving the milling of cobalt alloys in the *Stellite* 6 alloy. Bagci and Aykut (2006) improved the roughness of the piece by varying cutting speed, feed rate and depth of cut using the Taguchi optimization method. The statistical model related several input parameters, seeking to improve the output variables. The tool used in all tests had TiN coating, coated with PVD. The experiments were optimized with the parameters calculated for a reliability of 95% and the measured roughness ($R_a$) was 0.143 µm. Aykut et al., (2006) analyzed tool wear, cutting forces and chip morphology from optimizations in cutting parameters. Ninety experiments were performed with different cutting parameters. Uncoated and uncoated carbide tools (PVD) were used. With the aid of mathematical models, Aykut et al. (2007) optimized the values of cutting forces and workpiece roughness using different combinations of cutting speed, feed, and depth of cut, with uncoated carbide tools. After the experiments, they verified that the main influencer of the roughness was feed. Benghersallah et al. (2010) performed experimental tests with high cutting speeds using carbide inserts, varying cutting speed, feed, and depth of cut. The objective of this work was to compare the values of cutting force and tool wear for multiple combinations of input parameters. Regarding the tool, the progressive flank wear was dominant, while in some tests with higher speeds the presence of notch and chipping was observed.

Chavoshi (2013) used mathematical models to predict the roughness of the part by varying the cutting parameters, with inserts coated with TiN by PVD. After the studies, experimental confirmation was carried out to verify the consistency of the mathematical models. From the experiments, the parameters that most influenced tool wear were cutting speed and cutting depth, respectively. Yingfei et al. (2017) verified the influence of cutting parameters on tool wear, surface finish, residual stresses, and chip formation. They varied the cutting speed, feed rate and depth of cut, with carbide tools coated with TiAlN. They defined the specific cutting length (400 mm) for each evaluation on tool wear and roughness values. Feed speed contributed with 83% of influence on tool wear. The main wear mechanism was abrasion at low cutting speeds. Chipping, diffusion, and breakage were the most influential mechanisms for cutting speeds above 30 m/min. The parameters that most affected roughness was feed rate and cutting speed, with an influence of 57% and 38%, respectively. In alloy FSX 414, Folea et al. (2009) studied the influence of cutting speed, feed, and depth of cut. With coated carbide tools (Ti - PVD) and different combinations of cutting parameters, they measured the roughness of the piece after each pass. A statistical analysis was carried out to define the influence of the parameters on the quality of the surface finish.

## 3. Comparative Analysis of Techniques

In general, it appears that feed around 0.1 mm/rev (Sarikaya et al., 2016) and cutting speeds up to 60 m/min (Sarikaya & Güllü, 2015b) showed lower values for average roughness in the machining process of cobalt alloys. Some of the studies that showed lower roughness were performed using cutting fluid (Andhare et al., 2021; Saidi et al., 2019) and coated carbide inserts (Saidi et al., 2019). It was found that an alternative for good results in dry cutting would be the use of ceramic inserts (Ozturk, 2014; Sarıkaya et al., 2021). From the studies mentioned in this work, when machining cobalt alloys, for the lowest values for tool flank wear, cutting speeds below 45 m/min and feed rate around 0.1 mm/rev (Sarikaya et al., 2016). This being related to the use of coated carbide tools, using coolants, mainly by the MQL method (Andhare et al., 2021). However, when ceramic inserts are used, higher speeds could be used in dry cutting (Camana, 2019). Table 2 presents a summary of the machined materials, the input parameters, the output parameters, and the results obtained from the authors cited in this work.

Table 2. Summary of parameters and results related to the authors cited in this work.

| **Authors** | **Material** | **Input parameters** $v_c$ **(m/min),** $f$ **(mm/rev),** $a_p$ **(mm),** $v_f$ **(mm/min)** | **Lubri-cooling technique** | **Results** |
|---|---|---|---|---|
| | | **Turning** | | |
| Camana, 2019 | *Tribaloy* T-800 | $v_c$ between 90 and 140; $f$ = 0.15 and $a_p$ = 0.3 | Dry | $v_c$ = 89 m/min for lowest cost and 137 m/min for maximum production |
| Shao et al., 2013 | *Stellite* 12 | $v_c$ between 16.27 and 43; $f$ between 0.2 and 0.25; $a_p$ = 0.3 | | Coated tools showed lower $V_B$. $v_c$ lows: abrasion and adhesion. |
| Andhare et al., 2021 | *Haynes* 25 | $v_c$ between 19.77 and 70.22; $f$ between 0.033 and 0.117; $a_p$ between 0.329 and 1 | MQL | $v_c$ = 41.17 m/min, $f$ = 0.0593 mm/rev, $a_p$ = 0.329 mm, improvement of variables $R_a$, $V_B$ and $F_c$. |
| Sarikaya & Güllü, 2015a | | $v_c$ between 30 and 50; $f$ = 0.15; $a_p$ = 1 | 3 types of lubricants, varying the flow rate | Vegetable-based fluid at a flow rate of 180 mL/h, $v_c$ = 30 m/min for smaller $R_a$ and $V_B$ |
| Sarikaya & Güllü, 2015b | | $v_c$ between 15 and 60; $f$ between 0.12 and 0.16 | Dry/wet | $v_c$ = 45 m/min, $f$ = 0.12mm for smaller $R_a$ with wet |
| Sarikaya et al., 2016 | | $v_c$ between 15 and 60; $f$ between 0.08 and 0.16; $a_p$ = 1 | Dry, wet and MQL | Smaller $R_a$ with $v_c$ = 45 m/min, $f$ = 0.12 mm/ver, and MQL. Smaller $V_B$ with $v_c$ = 30 m/min and $f$ = 0.16 mm/rev, and MQL |
| Sarikaya et al., 2021 | | $v_c$ between 200 and 300; $f$ between 0.1 and 0.15 | Dry and MQL | Smaller $R_a$ with $v_c$ = 200 m/min, $f$ = 0.1 mm/rev and GR-NMQL |
| Bordin et al., 2014 | ASTM F-1537 | $v_c$ between 40 and 60; $f$ between 0.1 and 0.15; $a_p$ = 0.25 | Dry | Smaller $R_a$ with $f$ = 0.1 mm/rev and $v_c$ = 60 m/min |
| Bogajo et al., 2020 | | $v_c$ between 30 and 75; $f$ = 0.16; $a_p$ = 1 | Cryogenic | Smaller $R_a$ for $v_c$ < 60 m/min |
| Ozturk, 2014 | *Stellite* 6 | $v_c$ between 30 and 90; $f$ between 0.1 and 0.35; $a_p$ = 0.25 | Dry | Smaller $R_a$ for $v_c$ = 90 m/min, $f$ = 0.25 mm/rev, ceramic tool |
| Valíček et al., 2019 | | $v_c$ between 150 and 250; $f$ between 0.4 and 1; $a_p$ = 0.1 and 0.15 | | Mathematical model of roughness as a function of $v_c$, $a_p$ and $f$ |
| Saidi et al., 2019 | | $v_c$ between 30 and 80; $f$ between 0.08 and 0.16; $a_p$ between 0.15 and 0.45 | Wet | Combination of maximum MRR and lows $R_a$ and $F_c$: $v_c$ = 80m/min, $f$ = 0.16 mm/rev, $a_p$ = 0.45mm. Smaller $R_a$ with $v_c$ = 80 m/min, $f$ = 0.083 mm/rev, $a_p$ = 0.45 mm |

| | | | | |
|---|---|---|---|---|
| **Milling** | | | | |
| Bagci & Aykut, 2006 | *Stellite* 6 | $v_c$ between 50 and 90; $v_f$ between 100 and 180; $a_p$ between 0.25 and 0.75 | Dry | $v_c$ = 90 m/min, $f$ = 100 mm/min and $a_p$ = 0.25 mm for minor $R_a$ |
| Aykut et al., 2006 | | | | $F_c$ increased with the increase of $f$ and $a_p$ |
| Aykut et al., 2007 | | $v_c$ between 30 and 40; $v_f$ between 60 and 100; $a_p$ between 0.25 and 0.75 | | $R_a$ decreases with the combination of smaller $f$ and increase of $v_c$ |
| Yingfei et al., 2017 | | $v_c$ between 20 and 40; $v_f$ between 25 and 150; $a_p$ between 0.5 and 1.5 | | Smaller $R_a$ with $v_c$ = 40 m/min, $v_f$ = 25 mm/min and $a_p$ = 0.5 mm |
| Benghersallah et al., 2010 | | $v_c$ between 120 and 160; $f_z$ = 0.067 mm/z; $a_p$ = 0.3 | | Smaller $F_c$ with $v_c$ = 90 m/min. |
| Chavoshi, 2013 | | $v_c$ between 50 and 90; $v_f$ between 100 and 180; $a_p$ between 0.25 and 0.75 | | Smaller $R_a$ with increase of $v_c$ and decrease of $a_p$ |
| Folea et al., 2009 | FSX 414 | $v_c$ between 80 and 125; $f_z$ between 0.025 and 0.085 mm/z; $a_p$ between 0.25 and 0.85 | | Smaller $R_a$ with increase of $v_c$ and decrease of $f$ |

### *3.1 Difficulties in Machining Cobalt Alloys and Gaps in Research*

From the state of the art, the development of techniques to reduce the cycle time of both processes can be observed. The reduction in cooling time shortens the total cycle time, increasing the productivity of both processes. In addition, the rotational molding process still corresponds to a small portion of the polymer transformation sector, unlike the injection process, which is already widespread and even has mold performance simulation software. The cycle time and other features will be further covered in this section.

Cobalt alloys present variations between them, they can be linked mainly to chromium (Co-Cr), tungsten (Co-Cr-W), nickel (Co-Ni) and molybdenum (Co-Cr-Mo-WC). Such alloying elements impose some restrictions on machining processes:

I. The first difficulty deals with classification, most alloys have a hardness greater than 45 HRC, which can be considered hard machining.

II. The way the alloys are produced, casting or depositing on a substrate, is another stumbling block. Generally, measurements are restricted, hence the use of grinding processes for a final finish.

III. Hard materials tend to form a white layer on the surface due to chemical composition and process temperatures, which can affect the integrity and sub-surface of the part.

IV. Carbides are extremely hard, but the hardness is not uniform along the surface due to the inhomogeneous distribution of carbides, which impairs the performance of cutting tools with defined geometry.

V. The inhomogeneous crystalline structure, cobalt is allotropic, at room temperature is compact hexagonal (HC) changing its structure to face centered cubic (CFC) at 417 °C. The temperature at the time of cutting is not clear in the literature, thermographic analyzes estimate high values, however there are doubts regarding the numerical values determined.

VI. If the heat generated in the cutting zone can alter the metallographic phase, as well as the hardness, of the machined surfaces. This can influence residual stresses and surface hardness.

VII. Alloys show variation in carbon content. The higher the percentage, the formation of cobalt carbides in the structure of the machining zone subjected to high temperatures.

VIII. The higher carbon content leads to dense formation of carbides. The alloy will have a relatively low thermal conductivity, creating a relatively higher temperature in the cutting zone, which degrades the tool.

Among the gaps presented in the analyzed works, it is generally perceived that:

I. Using conservative cutting parameters is the most indicated, which compromises productivity.

II. Ceramic tools can perform well in terms of raising cutting parameters and productivity. However, such tools have higher values, which increases the cost of tooling.

III. The use of diamond and CBN tools was not found in the research.

IV. A thorough investigation is needed to clarify the interaction between lubricating coolant-tool coating-alloy chemical composition and cutting parameters.

V. In such noble materials, bold research is necessary, such as dynamic analysis in the cutting of hardened materials and their different phases depending on the chemical composition.

## 4. Conclusion

The present work made a brief review of the literature regarding turning and milling of cobalt alloys. The listed studies comprise aspects of tool wear and part roughness. The investigation contemplates the cutting parameters used, the lubrication and cooling conditions and the cutting tools. The main conclusions are:

The cutting parameters influence the results. The decrease in roughness was obtained with smaller feeds. Cutting speeds below 60 m/min are recommended when dry cutting with coated carbide tools.

To minimize flank wear in dry cutting, cutting speeds lower than 45 m/min and feeds lower than 0.1 mm/rev are recommended.

The adequate depth of cut to reduce tool wear and workpiece roughness, simultaneously, requires analysis according to the situation. For example, in turning with a depth of cut of 1 mm, low values of roughness and wear were obtained, regardless of the lubri-cooling medium. In dry milling such results were obtained with 0.5 mm depth of cut.

The application of cryogenic coolant and the MQL technique allow the use of higher cutting speeds in the machining of cobalt alloys when compared to traditional methods of lubrication, cooling and dry cutting.

Turning of cobalt alloys with ceramic inserts is a relevant and little-explored topic in the literature, especially in dry cutting.

Cobalt alloys are difficult to process, characterize and classify. Specific sectors make use of them, which restricts contact with these alloys on a day-to-day basis.

## References

Almeida, C. M. (2010). *Evaluation of TiN-coated carbide tool wear when milling hot-rolled and quenched/tempered ABNT4140 steel. Master's Thesis in Mechanical Engineering* (in Portuguese). Pontifical Catholic University of Minas Gerais, Belo Horizonte, Brazil.

Andhare, A. B., Kannathasan, K., & Funde, M. (2021). Optimization of Machining Parameters for Turning of Haynes 25 Cobalt-Based Superalloy. In Kalamkar V., Monkova K. (eds) Advances in Mechanical Engineering. *Lecture Notes in Mechanical Engineering* (pp. 703-710). Springer, Singapore. https://doi.org/10.1007/978-981-15-3639-7_84

ASM Handbook. (2004). *Metallography and Microstructures* (Vol. 9, eds.). George F. Vander Voort, Ohio, USA.

Astakhov, V. P. (2006). *Tribology of Metal Cutting* (Vol. 52). Great Britain: Elsevier Science.

Aykut, Ş., Bagci, E., Kentli, A., & Yazicioğlu, O. (2006). Experimental observation of tool wear, cutting forces and chip morphology in face milling of cobalt based super-alloy with physical vapour deposition coated and uncoated tool. *Materials & Design, 28*(6), 1880-1888. https://doi.org/10.1016/j.matdes.2006.04.014

Aykut, Ş., Gölcü, M., Semiz, S., & Ergür, H. S. (2007). Modeling of cutting forces as function of cutting parameters for face milling of satellite 6 using an artificial neural network. *Journal of Materials Processing Technology, 190*(1-3), 199-203. https://doi.org/10.1016/j.jmatprotec.2007.02.045

Bagci, E., & Aykut, Ş. (2006) A study of Taguchi optimization method for identifying optimum surface roughness in CNC face milling of cobalt-based alloy (stellite 6). *International Journal of Advanced Manufacturing Technology, 29*(9-10), 940-947. https://doi.org/10.1007/s00170-005-2616-y

Benghersallah, M.; Boulanouar, L., Le Coz, G., Devillez, A., & Dudzinski, D. (2010). Machinability of Stellite 6 hardfacing. *EPJ Web of Conferences, 6*, 5-12. https://doi.org/10.1051/epjconf/20100602001

Blau, P. J., Yao, M., Qu, J., & Wu, J. (2009). Use of multiple criteria to map the high-temperature scuffing behavior of Co-based superalloys. *Wear, 267*(1-4), 374-379. https://doi.org/10.1016/j.wear.2008.11.004

Bogajo, I. R., Tangpronpraser, T. P., Virulsri, C., KeeratihattayakorN, S., & Arrazola, P. J. (2020). A novel indirect cryogenic cooling system for improving surface finish and reducing cutting forces when turning ASTM F-1537 cobalt-chromium alloys. *International Journal of Advanced Manufacturing Technology, 111*(7-8), 1971-1989. https://doi.org/10.1007/s00170-020-06193-x

Bohatch, R., & Scheid, A. (2014). Microstructure and Properties of CoCrMoSi Alloy Coatings by PTA Weld Surfacing. *Technical contribution to the 2nd International Brazilian Conference on Tribology - TriboBR 2014*, November 3rd to 5th, 2014, Foz do Iguaçu, PR, Brazil.

Bordin, A., Bruschi, S., & GhiottI, A. (2014). The effect of cutting speed and feed rate on the surface integrity in dry turning of CoCrMo alloy. *Procedia CIRP, 13*, 219-224. https://doi.org/10.1016/j.procir.2014.04.038

Bordinassi, E. C., Stipkovic, M. F., BatalhA, G. F., Delijaicov, S., & Lima, N. B. (2006). Superficial integrity analysis in a super duplex stainless steel after turning. *Journal of Achievements in Materials and Manufacturing Engineering, 18*(1-2), 335-338.

Camana, M. (2019). Life analysis of cutting tools in the turning process of Tribaloy T800 steel using ceramic inserts. *Monograph in Mechanical Engineering* (in Portuguese), University of Caxias do Sul - UCS, Caxias do Sul, Brazil.

Chavoshi, S. Z. (2013). Modelling of surface roughness in CNC face milling of alloy stellite. *International Journal of Computational Materials Science and Surface Engineering, 5*(4), 304-321. https://doi.org/10.1504/IJCMSSE.2013.059121

Chetan, G., S., Venkateswara, & Rao, P. (2015) Application of sustainable techniques in metal cutting for enhanced machinability: A review. *Journal of Cleaner Production, 100*, 17-34. https://doi.org/10.1016/j.jclepro.2015.03.039

Corrêa, J. G. (2019). *Machinability and integrity of the machined surface in turning superduplex, triplex and supermartensitic stainless steels* (Doctoral Thesis in Mechanical Engineering (in Portuguese), Federal University of Santa Catarina, Florianópolis, Brazil).

Davim, J. P. (2008). *Machining: Fundamentals and Recent Advances*. Aveiro, Portugal: Springer-Verlag.

Durejko, T., Łazińska, M., Dworecka-Wójcik, J., Lipiński, S., Varin, R. A., & Czujko, T. (2019). The Tribaloy T-800 Coatings Deposited by Laser Engineered Net Shaping (LENSTM). *Materials, 12*(9), 1366-1379. https://doi.org/10.3390/ma12091366

Folea, M., Schlegel, D., Lupulescu, N. B., & Parv, L. (2009). Modeling surface roughness in high-speed milling: Cobalt based superalloy case study. *Proceedings of the 1st International Conference on Manufacturing Engineering*, *Quality and Production Systems*, MEQAPS '09, 2, 353-357.

Geddes, B., Leon, H., & Huang, X. (2010). *Superalloys: Alloying and Performance*. ASM International. Ohio, USA. https://doi.org/10.31399/asm.tb.sap.9781627083133

Hasan, M. S., Mazid, M. A., & Clegg, R. E. (2016). The Basics of Stellites in Machining Perspective. *International Journal of Engineering Materials and Manufacture, 1*(2), 35-50. https://doi.org/10.26776/ijemm.01.02.2016.01

Haynes. Retrieved on October 9, 2021, from https://haynesintl.com

Jebaraj, A. V., Ajaykumar, L., Deepak, C. R., & Aditya, K. V. V. (2017). Weldability, machinability and surfacing of commercial duplex stainless steel AISI2205 for marine applications - A recent review. *Journal of Advanced Research, 8*(3), 183-199. https://doi.org/10.1016/j.jare.2017.01.002

Krolczyk, G. M., Maruda, R. W., Krolczyk, J. B., Nieslony, P., Wojciechowski, S., & Legutko, S. (2018). Parametric and nonparametric description of the surface topography in the dry and MQCL cutting conditions. *Measurement, 121*, 225-239. https://doi.org/10.1016/j.measurement.2018.02.052

Machado, A. R., Abrão, A. M., Coelho, R. T., & Silva, M. B. (2009). *Material Machining Theory* ($3^a$. ed.). São Paulo: Blücher. (in Portuguese)

Oliveira, L. G., Oliveira, C. H., Brito, T. G., Paiva, E. J., Paiva, A. P., & Ferreira, J. R. (2020). Nonlinear optimization strategy based on multivariate prediction capability ratios: Analytical schemes and model validation for duplex stainless steel end milling. *Precision Engineering, 66*, 229-254. https://doi.org/10.1016/j.precisioneng.2020.06.005

Ozturk, S. (2014). Machinability of Stellite-6 Coatings with Ceramic Inserts and Tungsten Carbide Tools. *Arabian Journal for Science and Engineering, 39*(10), 7375-7383. https://doi.org/10.1007/s13369-014-1343-9

Paiva, J. M. F., Torres, R. D., Amorim, F. L., Covelli, D., Tauhiduzzaman, M., Veldhuis, S., … & Fox-Rabinovich, G. (2017). Frictional and wear performance of hard coatings during machining of super duplex stainless steel. *The International Journal of Advanced Manufacturing Technology, 92*(1-4), 423-432. https://doi.org/10.1007/s00170-017-0141-4

Policena, M. R., Devitte, C., Fronza, G., Garcia, R. F., & Souza, A. J. (2018). Surface roughness analysis in finishing end-milling of duplex stainless steel UNS S32205. *The International Journal of Advanced Manufacturing Technology, 98*(5-8), 1617-1625. https://doi.org/10.1007/s00170-018-2356-4

Saidi, R., Fathallah, B. B., Mabrouki, T., Belhadi, S., & Yallese, M. A. (2019). Modeling and optimization of the turning parameters of cobalt alloy (Stellite 6) based on RSM and desirability function. *International Journal of Advanced Manufacturing Technology, 100*(9-12), 2945-2968. https://doi.org/10.1007/s00170-018-2816-x

Santos, S. C., & Sales, W. F. (2007). Tribological Aspects of Material Machining (in Portuguese). 1ª. Artliber (ed.).

SarikayA, M., & Güllü, A. (2015a). Multi-response optimization of minimum quantity lubrication parameters using Taguchi-based grey relational analysis in turning of difficult-to-cut alloy Haynes 25. Journal of Cleaner Production, 91, 347-357. https://doi.org/10.1016/j.jclepro.2014.12.020

SarikayA, M., & Güllü, A. (2015b). The Analysis of Process Parameters for Turning Cobalt-Based Super Alloy Haynes 25/L 605 Using Design of Experiment. *Solid State Phenomena, 220-221*, 749-753. https://doi.org/10.4028/www.scientific.net/SSP.220-221.749

Sarikaya, M., Yilmaz, V., & Güllü, A. (2016). Analysis of cutting parameters and cooling/lubrication methods for sustainable machining in turning of Haynes 25 superalloy. *Journal of Cleaner Production, 133*, 172-181. https://doi.org/10.1016/j.jclepro.2016.05.122

Sarikaya, M., Şirin, Ş., Yildirim, Ç. V., Kivak, T., & Gupta, M. K. (2021). Performance evaluation of whisker-reinforced ceramic tools under nano-sized solid lubricants assisted MQL turning of Co-based Haynes 25 superalloy. *Ceramics International, 47*(11), 15542-15560. htpps://doi.org/10.1016/j.ceramint.2021.02.12

Scheid, A. (2007). Study of degradation mechanisms for the development of alloys for galvanizing pot components. *Doctoral Thesis in Materials Science* (in Portuguese). Federal University of Paraná, Curitiba, Brazil.

Shao, H., Li, L., Liu, L. J., & Zhang, S. Z. (2013). Study on machinability of a stellite alloy with uncoated and coated carbide tools in turning. *Journal of Manufacturing Processes, 15*(4), 673-681. https://doi.org/10.1016/j.jmapro.2013.10.001

Sharma, V. S., Dogra, M., & Suri, N. M. (2009). Cooling techniques for improved productivity in turning. *International Journal of Machine Tools and Manufacture, 49*(6), 435-453. https://doi.org/10.1016/j.ijmachtools.2008.12.010

Shokrani, A., Dhokia, V., & Newman, S. T. (2016). Cryogenic high-speed machining of cobalt chromium alloy. In *7th HPC 2016 - CIRP Conference on High Performance Cutting, 46*, 404-407. https://doi.org/10.1016/j.procir.2016.04.045

Stellite. Retrieved October 9, 2021, from https://www.stellite.com

Tavakoli, A., Liu, R., & Wu, X. J. (2008). Improved mechanical and tribological properties of tin-bronze journal bearing materials with newly developed Tribaloy alloy additive. *Materials Science and Engineering A, 489*(1-2), 389-402. https://doi.org/10.1016/j.msea.2007.12.030

Tschätsch, H. (2008). Applied Machining Technology (8ª ed.). Berlin, Heidelberg: Springer Berlin Heidelberg

Valíček, J., Řehoř, J., Harničárová, M., Gombár, M., Kušnerová, M., fulemová, J., & Vagaská, A. (2019). Investigation of surface roughness and predictive modelling of machining Stellite 6. *Materials, 12*(16), 2551-2574. https://doi.org/10.3390/ma12162551.

Yingfei, G., De Escalona, P. M., & Galloway, A. (2017). Influence of Cutting Parameters and Tool Wear on the Surface Integrity of Cobalt-Based Stellite 6 Alloy When Machined Under a Dry Cutting Environment. *Journal of Materials Engineering and Performance, 26*(1), 312-326. https://doi.org/10.1007/s11665-016-2438-0

Youssef, H. A. (2016). *Machining of Stainless Steels and Super Alloys: Traditional and Nontraditional Techniques*. John Wiley & Sons, Alexandria, Egypt. https://doi.org/10.1002/9781118919514

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