Review

Machinability of nickel-based superalloys using ceramic tools

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Abstract: Nickel-based superalloys are attractive to many industrial sectors (automotive, military, energy, aerospace etc.). However, their physical properties make them difficult to machining using traditional tools. Therefore, the new materials for the machining of Ni-based alloys are required. Ceramic-based composites could act as a tool to replace the current materials. The incentives for this paper are to provide an overview of existing ceramic composites and draw some conclusions that will help in solving the problem of choosing materials for processing of Ni-based superalloys. Despite the diversity of ceramic composites in this work the focus was on the SiAlON ceramic.

Keywords: nickel-based superalloys; ceramic instruments; carbides; cubic boron nitride; cermet; SiAlON

1. Introduction

Superalloys show high strength, corrosion or oxidation resistance at elevated temperatures, and creep resistance [1-4]. The most classic type of the superalloy is nickel-based superalloys are mainly used for aerospace, oil and gas mining, petrochemical, and other industrial sectors [5-7]. Table 1 presents various categories, compositions and properties of nickel-based superalloys [8].

Table 1. Various categories, compositions and properties
of nickel-based superalloys.

superalloys		
Inconel 718	Ni 54.48, Cr 17.50, Fe 22.3, Nb 4.90, Al 0.66, Ti 0.96	Precipitation hardenable, high creep-rupture strength at high temperatures to about 700°C and excellent strength. Precipitates of primary niobium carbide (NbC), titanium carbide (TiC) disk-shaped gamma double prime (γ'') precipitates (Ni$_3$Nb), and needle-like precipitates of δ (Ni$_3$Nb) present
Inconel 100	Ni 60, Cr 10, Co 15, Mo 3, Al 5.5, Ti 4.7, C 0.18, B 0.014, Zr 0.06	Precipitation hardenable, high rupture strength through 870°C. The high percentages of titanium, aluminum, and low refractory metal increase strength-to-density ratio
Inconel 825	Ni 37.1, Fe 32.2, Cr 22.8, Mo 3.24, Cu 2.07, Ti 0.859, C 0.0155	Good resistance to pitting, intergranular corrosion, chloride-ion stress-corrosion cracking, and general corrosion in a wide range of oxidizing and reducing environments
IN-713LC	Ni 74.2, Cr 12.6, Mo 4.9, Nb 1.96, Al 5.7, Zr 0.1, Ti 0.63, C 0.047, B 0.007	Good combination of tensile and creep-rupture properties as a result of gamma-prime strengthening enhanced by solid solution and grain-boundary strengthening, and good castability
Udimet 720LI	Ni 57.4, Cr 16, Co 15, Mo 3, Ti 5, Al 2.5, W1, C 0.1	Solid solution strengthened with tungsten and molybdenum and precipitation-hardened with titanium and aluminum. High strength, excellent impact strength retention at elevated temperatures, good oxidation and corrosion resistance, and high degree of work hardening
FGH95	Ni 62.5, Cr 12.98, Co 8.00, Nb, 3.50, Al 3.48, Ti 2.55, W 3.40, Mo 3.40, C 0.060, B 0.012	Precipitation hardened having higher tensile and yield strength at 650°C. A compact structure after hot isostatic pressing (HIP) consisting of coarse gamma prime phase (γ') precipitated along previous particle boundaries (PPB) appear in the grain
ME-16	Ni 56.3, Cr 10.4, Co 20.5, Al 3.1, Ti 2.6, W 3, Ta 1.4, Mo 1.3, Nb 1.4	Good strength and creep resistance at high temperatures (600–800°C). Good resistance to fatigue crack initiation at the lower temperatures (300–600°C). Can maintain strength and lower density at elevated temperature
RR1000	Ni 52.4, Cr 15, Co 18.5, Mo 5, Ti 3.6, Al 3, Ta 2, Hf 0.5, C 0.03	Solid solution strengthened with chromium, molybdenum, and cobalt. Good strength, good toughness, creep resistance, good oxidation, and corrosion resistance at high temperature
Nimonic C-263	Ni 51.0, Cr 20.0, Co 20.0, Mo 5.8, Ti 2.2, Al 0.5	A readily weldable, age-hardenable superalloy with excellent strength, ductility, and corrosion resistance up to around 850°C. Molybdenum for solid-solution strengthening
Nimonic 105	Ni 54.0, Co 20.0, Cr 15.0, Mo 5.0, Al 4.7, Ti 1.3	An age-hardenable superalloy within creased aluminum for improved oxidation-resistance and strength, and high creep-rupture properties up to around 950°C. Strengthened by additions of molybdenum, aluminum, and titanium
Nimonic 75	Ni 80.5, Cr 19.5	Good corrosion and heat resistance, high-temperature strength, and outstanding oxidation-resistance
Nimonic 80 A	Ni 76.0, Cr 19.5, Ti 2.4, Al 1.4	An age-hardenable creep-resistant alloy for service at temperatures up to around 815°C

Hastelloy alloy C-2000	Ni 47, Cr 22, Fe 18, Mo 9, Co 1.5, W 0.6	Localized corrosion resistance, good resistance to hot acids, and excellent resistance to stress-corrosion cracking
Haynes 282	Ni 57, Cr 20, Co 10, Mo 8.5, Ti 2.1, Al 1.5, Fe 1.5, Mn 0.3, Si 0.15, C 0.06, B 0.005	γ' precipitation strengthened nickel-based superalloy along with excellent creep properties, fabricability, and thermal stability

However, despite the exceptional properties of Ni-based superalloys, the problem of machining continues of exist due to their high strength and plastic viscosity [9-11]. There is a series of problems relating to conventional machining of Ni-based superalloys including the following:

• Due to the low thermal conductivity, the heat generated during processing is not transferred to the chips or the workpiece, but is concentrated on the cutting edges, which leads to crater wear and extensive plastic strain of the cutting tool edge.

• Increased crater wear results in catastrophic failure of cutting instrument and plastic strain causes high cutting forces.

• Metal pick-up and coating delamination due to chemical reaction of Ni-based superalloys during machining reduces tool life.

• High abrasive wear on the cutting edge of the tool because of the presence of hard and abrasive intermetallic compounds in the microstructure of these alloys.

• Changes in the microstructure of the alloys due to high heat generation during machining and generated residual stresses cause a further reduction in the fatigue life of the component.

• In addition, the machining of these alloys also leads to high cutting emulsion consumption, cost of which corresponds to cost of cutting instruments [12].

Based on the above-listed drawbacks the manufacturers are interested in minimizing the losses at all stages in the processing chain. Therefore, new tool materials or other technical solutions for Ni-based superalloys machining are needed. Use of ceramics as a cutting tool could be proposed as a possible solution to these challenges.

Ceramic tool materials exhibit very high hardness and wear resistance, high resistance to plastic deformation, and chemical stability. The diversity of ceramic tool grades appearing each year on the market indicates that these materials are promising. Ceramic tools used for broad range of materials and processing operations, including also high-speed finishing machining of superalloys.

The most promising group of ceramic materials for machining of Ni-based superalloys is mixed nitride and oxide ceramic, namely SiAlON. In our previous article we provided basic information about this type of materials. Briefly, Si-AlONs are formed when silicon nitride (Si_3N_4), aluminum oxide (Al_2O_3), and aluminum nitride (AlN) react together. α-Si-AlON and β-SiAlON represent the two main phases of this

type of ceramic. Each phase features its own properties, which can be contributed to the composites [13].

This review paper provides an overview of ceramic tools for machining of nickel-based superalloys including effect of cutting parameters, using of coolant supply and the integrity of machined surface. Special attention was focused on SiAlON ceramic as the currently most promising candidate for the processing of these alloys.

2.   Type of tool materials for machining nickel-based alloys

It should be noted in the analysis of publication activity over the last 20-30 years the growing interest of the scientific community to the use of effective solutions for the treatment of heat-resistant nickel-based alloys.

By increasing efficiency, researchers basically mean an increase in cutting conditions (cutting speed, feed) without losing the quality of the machined surface.

Usually, the authors distinguish 3 groups of tool materials that are applicable for processing nickel-based alloys:

- carbide - representing the interaction of tungsten carbide (WC) / titanium carbide (TiC) / tantalum carbide (TaC) and a binder component - cobalt (Co) including those with wear-resistant PVD / CVD nitride or carbonitride multilayer coatings [14-16];
- boron nitride having to the cubic structure (CBN) [17];
- ceramic instruments are solid solutions of variable composition formed on the basis of Al_2O_3 or Si_3N_4 [18-24].   Next, consider the details of each of them.

2.1   Carbide for machining nickel-based alloys

The use as a cutting tool of carbide when processing nickel-based HRSA due to their high ratio of hardness, tensile strength and fracture toughness [25].

R. Arunachalam et al. [26] observed that the basic research of physical and mechanical, chemical and performance properties of carbide instruments during turning and milling of various structural materials, including difficult-began at the turn of 70s - 80s 20th century [27]. In addition, it is noted that these studies have not been interrupted and are being conducted now.   Prolonged and systematic research carbide instruments allowed to use this tool in the industry in the processing of nickel-based HRSA cutting as the main material.

Koseki S. et al. [28] performed a comprehensive analysis of damage analysis of carbide instruments with commercial TiN PVD-coated at turning Ni-based superalloy (Inconel 718) [21]. Electron probe microanalysis (EPMA), scanning electron microscopy (SEM) and transmission electron microscopy (TEM) analyzes showed that the treated material is mechanically adhered to the tool, but there are no chemical bonds.

These facts confirm the absence diffusive and oxidative deterioration. The authors noted that the development of extended wear in places of micro-defects in the form of pores and voids in the coating. Thus, it is necessary to lowest such defects.

Zihua Hu et al. [29] suggested using the rake face chemical-mechanical polishing (CMP) to improve the cutting performance and the tool life. The study showed that in turning GH4169 nickel-based superalloy, this method made it possible to reduce the components of the cutting forces Fx, Fy and Fz by 18.26%, 11.37% and 13.81%, respectively, and the service life compared to the insert without processing by 35.92%.

At the moment, the main vector of development of carbide instruments is aimed at using complex-structured multifunctional wear-resistant coatings [30-32].

A.S. Vereschaka et al. [30] note that the architecture of multilayer wear-resistant coatings should be designed based on the properties of the material being processed. First, an intermediate high-adhesion layer must be applied, and then functional layers, which make it possible to resist abrasive and diffusion wear during the turning process.

2.2 *Cubic boron nitride for machining nickel-based alloys*

The use of cubic boron nitride (CBN) as a cutting tool in the processing of heat-resistant nickel alloys is poorly understood. Basically, CBN used in the treatment of increased material hardness (45-60 HRC), such as hardened steel [33] or ductile iron [34, 35].

Costes J.P. et al. [16] proposed the use of Inconel 718 for processing as a cutting tool cubic boron nitride (CBN), instead of the carbide. It was noted that the main causes of tool wear at processing CBN nickel alloys is the adhesion and diffusion, due to their chemical affinity, as well as conventional abrasion. The formation of wear along the front surface was observed, as well as uneven wear along the front surface in the form of a dimple, caused by thermal effects from the edge to the center.

R.M. Arunachalam et al. [36] note that in the process of turning nickel-based alloys diffusion of Nb, Cr, Fe and Ni from the workpiece into the tool occurs. Mutual diffusion was observed not in the entire volume of the material, but in certain areas, which allowed them to conclude that certain conditions were created during the cutting process, in which the chemical reaction between the tool and the processed materials was minimal.

Harris T.K. et al. [37] in their work tried to find a relationship between the CBN content, the TiC/TiN bonding phases, the grain size (1-15 μm) and the physical and mechanical properties of the tool (hardness / temperature). As an evaluation method using Vickers indentation method by heating under various conditions.

Kaya E. et al. [38] conducted a study of the development of wear of polycrystalline diamond (PCD) and cubic boron nitride (CBN) tools during high-speed (cutting speed Vc = 70-250 m/min) turning of NiTi alloys. It was found that both tool materials are sensitive to increased cutting speed. At cutting

speeds up to Vc = 130 m / min, the dominant wear is adhesion wear and abrasion along the insert main flank surface caused by mechanical stress. By increasing, the cutting speed was observed thermal effects mainly grains chipping from the front surface. Thus, the observed diffusion, chemical and oxidative types of wear, leading to premature failure of the CBN. This study allows us to conclude that there is a limited increase in cutting speed due to its physical and mechanical characteristics.

2.3   Ceramic instruments for machining nickel-based superalloys

Ceramic tool materials in the processing of difficult-to-machine steels and alloys are slowly replacing hard alloys due to their physical and chemical properties [3].

Tool ceramics are used for a wide range of operations and materials, including high-speed finishing of high-temperature alloys. The specific properties of nickel-based heat-resistant alloys when properly used can provide high productivity.

The variety of instrument grades of ceramics and compositions appearing on the market every year makes it possible to assert the promise and interest in the material. Currently, ceramic cutting tools (ceramic inserts) are mainly represented by NTK Cutting tools (USA), NikkoTools (Italy), Sandvik Coromant (Sweden), ISCAR (Israel), Tungaloy Corporation (Japan), CeramTec (Germany) and others. Silicon nitride- and alumina-based ceramics holds a special place in processing of Ni-based superalloys.

Jun Zhao [39] identified 4 groups of instrumental materials in his work: Al_2O_3-based ceramics, Si_3N_4-based ceramics, SiAlON-based ceramics and ceramic matrix composites. He notes the growing need ceramic instruments and highlights the stages of development from 1938 to the present day. One of the most promising ceramic materials for efficient turning Nickel-Based HRSA is Al_2O_3 with the addition of TiC and other hard particles such as TiN, (W, Ti) C, Ti (C, N), TiB_2 and SiCw. Table 2 presents various categories, compositions and properties of Al_2O_3-based ceramic instruments for turning hardened steels and heat-resistant alloys.

Table 2. Various categories, compositions and properties of Al_2O_3-based ceramic instruments for turning hardened steels and heat-resistant alloys.

Composite	Producer/Contry	Grade	Density (g·cm⁻³)	Hardness (HRA)	Flexural strength (MPa)	Fracture toughness (MPa·m$^{1/2}$)	Applications
$Al_2O_3/(W,Ti)C$	Shandong University (China)	AT	4.6	2040HV	820	7.4	
	Shandong University (China)	SG-4	6.65	94.7-95.3	850	4.94	Machining hardened steels
	Shandong University (China)	FG-2(graded)		94.7-95.5	830		
	Shandong University (China)	AWT10	6.65	2350HV	930	7.55	
$Al_2O_3/WC/TiC_n$	Shandong University (China)	LWT-1	6.5	2340HV	840	7.87	
Al_2O_3/SiC_w	Shandong University (China)	JX-1	3.63	94-95	800	8.5	
	Sandvik Coromant (Sweden)	CC670	3.74	2000HV	900	8.0	Machining heat-resistant alloys
	Kennametal (USA)	KY4300	3.74	2000HV	700	7.7	
$Al_2O_3/TiB_2/SiC_w$	Shandong University (China)	LP-2	3.94	94-95	700-800	7.8	

Li Xikun et al. in their review highlighted a line of commercial and experimental Si_3N_4-based ceramic instruments for processing difficult-to-machine alloys due to their high thermal resistance, high thermal conductivity, low coefficient of thermal expansion and fracture toughness. Table 3 presents various categories, compositions and properties of Si_3N_4-based ceramic instruments [18, 39].

Table 3. Various categories, compositions and properties of Si_3N_4-based ceramic instruments.

Brand	Composition	Hardness (HRA)	Bending strength (GPa)	Density (g·cm⁻³)	Fracture toughness (MPa·m$^{1/2}$)	Company/Country
HDM1	Si_3N_4 matrix	92.5	0.93			China
HDM2	Si_3N_4 matrix, SiC_w fiber	93	0.98			
HDM3	Si_3N_4 matrix	92.5	0.83			
N55555	Si_3N_4 matrix	(≥96.5)				
CC680	Si_3N_4- Al_2O_3- Y_2O_3	93.5~94.5	1.0~1.3			Sandvik Coromant (Sweden)
KY3000	$77\%Si_3N_4$-$13\%Al_2O_3$-$10\%Y_2O_3$	1800 (HV)	1.0~1.3			Kennametal (USA)
Kyon2000	No pressure sintered Sialon	1800 (HV)	765	3.2~3.4	6.5	USA
Quantum5000	Hot pressing Si_3N_4-TiC	93.5	750	3.4	4.3	
Lsay	Hot pressing Si_3N_4+ Y_2O_3	2150 (HV)	714	3.2		
SX7		93.0	1100		7.0	Japan
FX920		92.8	960	3.27	9.4	
FX910		94.7	760	3.32	6.7	
Naycon		92.8	1000	3.23		
NCT	Hot pressing Si_3N_4	92.6	816	3.3	6.7	Germany
KY1540	α/β-SiAlON	18.24		3.35	7.45	Kennametal (USA)

3. Features of SiAlONs and their application in the processing of nickel-based HRSA

As it is known, nickel alloys are very difficult to cut materials due to high chemical affinity and poor thermal conductivity that they have in conjunction with the presence of hard-abrasive carbides in their microstructure and the work-hardening that occurs during machining. For this reason, in order to carry out efficient machining of this type of alloys, it is

necessary to select the appropriate cutting tool and define the most optimal machining parameters for the tool-part pairs.

Unfortunately, high-speed machining of nickel alloys using cemented carbide, results in a weakness of the cutting tools characteristics mainly due to the occurring ultra-high local temperature that leads to the reduction in tool life.

In mass production, the use of high-speed machining is essential. Unfortunately, this type of machining for nickel alloys using cemented carbide is not feasible due to the loss of the cutting tools characteristics mainly related to the ultra-high local temperature that occurs in the tool-part contact zone, which leads to a reduction in the useful life of the tool. One of the ways to solve the negative effects that happened by machining of nickel alloys at high cutting speeds is the use of ceramic cutting tools, which can keep for a long time even at high temperatures, their chemical stability and high wear resistance and hardness.

SiAlON was developed in the 1970s and prepared by hot pressing with Si_3N_4 as hard phase, Al_2O_3 as abrasion resistance phase and a small amount of Y_2O_3 as sintering aids. SiAlON are formed when silicon nitride (Si_3N_4), aluminium oxide (Al_2O_3) and aluminium nitride (AlN) are reacted together.

SiAlON cutting tools have some special features such as good fracture toughness, hardness (even at high temperatures) and resistance to sudden temperature changes, which make it a suitable material for machining of various difficult to cut materials including nickel alloys. $Si_xAl_xO_xN_x$ is characterized by high chemical inertness and low coefficient of thermal expansion, therefore, when cutting, there is a more uniform and predictable wear, without grooves and chipping.

There are several kinds of SiAlON ceramics as an example α-SiAlON, β-SiAlON and their combination ($\alpha+\beta$). The most commonly used compositions at present are β-SiAlON and ($\alpha+\beta$) SiAlONs, which contain a substantial excess of sintering aids. However, the field is still changing with compositions developing to suit specific applications.

3.1. α- SiAlON

α-SiAlONs are isostructural with α-Si_3N_4 where m (Si-N) bonds are replaced by m(Al-N) bonds and n(Si-N) bonds by n(Al-O) bonds. Crystal structure of α-SiAlONs requires an extra cation for stability. Formula of the α-Sialons is $M_x^{v+}Si_{12-m-n}Al_{m+n}O_nN_{16-n}$, where M can be Li, Mg, Ca, Y and/or a rare earth element, depending on its ionic radius [40] or with using quenching. Some larger cations can enter the structure only in combination with other cations. The x value (x = m/v) is mostly between 0.3 and 1.0. The α-SiAlON phase (especially with high x) is stable only at high temperatures and transform to β-Sialon and other crystalline or glassy phases by heat treatment.

The α-SiAlONs are very attractive because of their hardness and the ability to improve high-temperature properties by reducing the amount of residual glassy phase, but these materials are brittle, and improved fracture toughness is desirable without significant reduction of the hardness. Ekström

in his work [41] described some results about α-SiAlON, which can be summarized as follows:

1. Dense α-SiAlONs may act as the matrix in composite materials with SiC-whiskers or $MoSi_2$-particulates. Chemical compatibility is good, but with SiC the toughness was not significantly improved and with $MoSi_2$ the drop in hardness was unacceptable.

2. The rare earth elements with large ion sizes (i.e. Sm and Nd) cannot be used to stabilize α-phases in ceramics used at high temperatures, because these α-phases decompose at ~1000-1650°C. These ceramics should be used at low temperatures.

3. Yttrium and the rare earth elements with small ion sizes (i.e. Yb and Dy) form α-phases that are stable at high temperatures, and these additives are very usefull for future α-SiAlONs ceramics at all temperatures.

In order to prolong the useful life of the α-SiAlON-based cutting tool, different works have been developed based on the addition of different phases to the ceramic structure. For example, Salomon et al. and Rosenflanz et al. [42, 43] prepared and developed new ceramic cutting tools on the base of α-SiAlON with other complementary phases, which provide a significant improvement in the mechanical properties and chemical resistance. Table 4 shows the mechanical properties and tool lives obtained in this work.

Table 4. Mechanical properties and tool lives obtained in [42]

Sample	Composition	Minor phases	HV1 (GPa)	K_{1C} (MPa·m$^{1/2}$)	Tool life (min)
A039 - HIP1	α-Sialon	-	20.2±0.5	6.8 ± 0.3	17.5
A039 – HIP1	α-Sialon	Y_2O_3, $La_5Si_3NO_{12}$, $Y_{10}Al_2Si_3O_{18}N_4$	14.2±0.5	6.2±0.2	20.4
A057 – HIP1	α-Sialon	$SiAl_6O_2N_6$, Y_2O_3, La_2O_3	17.0±0.5	6.7±0.2	31.0
A057 – HIP3	β-Sialon, α-Sialon	$SiAl_6O_2N_6$	15.1±0.5	6.7±0.2	20.0
A057 – HIP4	α-Sialon	$SiAl_6O_2N_6$	17.7±0.7	6.2±0.3	27.5
B069 – HIP3	β-Sialon	-	14.4±0.2	7.0±0.3	23.3
A039 – HIP5	β-Sialon	$SiAl_6O_2N_6$	19.7±0.5	6.9±0.1	-

The best results were obtained for the samples A057 - HIP1, A057 - HIP4 and B069 –HIP3 because the tool life is longer than usually obtained for the β-Si_3N_4 cutting tools (with keeping other important requirements as roughness of workpiece etc.). The sample A039 – HIP5 was used to compare the phase composition of two differently cooled samples. Scientists found that the presence of defects and polytype 21R

($SiAl_6O_2N_6$) has a negative influence on cutting performance. However, the presence of homogeneity of the microstructure and pure α-SIAlON and β-SIAlON with good ratio between elongated and submicron grains provide positive influence on cutting performance. Moreover, authors determined that pure α- or β-SIAlONs have better cutting performance compared with β-Si3N4; that inhomogeneities and polytype 21R have higher effect on cutting performance than on macro-mechanical properties (HV1, K_{1c}10); and that it is possible to change the phase composition just by modification of the cooling rate (A039 – HIP 1 vs. A039 HIP 5).

3.2. β-SiAlON

β-Sialon are formed by substituting Si in the β-Si_3N_4 structure by Al provided valence compensation by replacement equivalent concentration of N by O. A general formula of β-SIAlONs is $Si_{6-z}Al_zO_zN_{8-z}$, with $0<z<4.2$, where z (Si-N) bonds are replaced by z (Al-O) bonds [40]. β-SiAlONs are isostructural with β-Si_3N_4. β-SiAlON ceramics are promising materials for applications involving high temperatures, highly corrosive environments, and high mechanical stress because they exhibit high strength retention and high thermal shock resistance at elevated temperatures as well as good erosion resistance and low creep [44-48]. Compared with Si_3N_4, β-SiAlON ceramics are not only easily sintered and fabricated but also can be easily combined with other materials to strengthen or improve the properties of ceramics [49-50].

β-SIAlON ceramics dominated the early interest because they could be pressurelessly sintered into complex shapes, and the resulting materials had a good combination of properties; for example, some pressurelessly sintered β-SIAlON ceramics have strengths of up to 1000 MPa and fracture toughnesses of up to 8 MPa·m$^{1/2}$ [51].

Due to its high mechanical characteristics, recently the β-SIAlON has been used even in additive technologies to obtain parts with complex spatial shapes, for instance, Tian et al. [52], used Si_3N_4, Al_2O_3 and AlN particles as raw materials for the design of β-SiAlON ceramics with different main crystal phases. In this work, the green body of the β-SiAlON-matrix ceramic samples were obtained by using stereolithography (SLA) additive manufacturing. After degreasing, dense β-SiAlON ceramics with different SiAlON phases were fabricated through gas pressure sintering at 1800 °C for 1 hour at 3 GPa. Moreover, the authors studied the effects of the different Al_2O_3 contents on the shrinkage, phase composition, relative density, microstructure, mechanical property and hardness. The obtained results indicate that the main phase of the ceramics was β-SiAlON and the specific chemical compositions of it were Si_5AlON_7, $Si_{3.1}Al_{2.9}O_{2.9}N_{5.1}$ and $Si_2Al_4O_4N_4$, with mainly intergranular phases of $Y_3Al_5O_{12}$, $YAlO_3$ and Al_2O_3. The sintered β-Si_5AlON_7 ceramics had a relative density of 90.03 %, with Vickers hardness (HV5), bending strength and fracture toughness of 16.7 GPa, 465 MPa and 4.84 MPa·m$^{1/2}$, respectively. Meanwhile, the shrinkage of the materials was 28.7 %.

Dense β-sialon ceramics with low z values (z~1) have microstructures consisting of elongated crystals and grain boundary glass, and of all the various sialon materials, show the highest observed fracture toughness values at room temperature; however, their hardness is relatively low (14–15 GPa) partly because of the residual grain boundary glass (~10 GPa) [53]. Because of this, in cutting tools β-SIAlON is used as a reinforce phase that provides strength and toughness.

3.3. (α+β) SiAlON

The α-β SiAlON combinations with a minimum of glassy phase, are currently the most promising materials for further use, both at low and high temperatures [41].

The hardness of β-sialon ceramics is relatively low (14–15 GPa), in contrast, α-sialon ceramics generally have equiaxed grains and show an excellent hardness (~22 GPa), much higher than that of any other sialon ceramics. The properties of mixed α/β-sialon ceramics can be optimised by adjusting the proportion of the two phases, and this can be done by changing the starting composition [54]. A high content of β- sialon yields high strength and toughness, whereas a high proportion of the α-sialon phase gives excellent hardness. Mixed α/β-sialon ceramics can be produced with very little intergranular glass and so their wear resistance, strength and especially creep resistance at high temperatures are greatly improved [53]. For instance, with a α-β ratio around 50:50 it is possible to prepare very hard (HV10 around 22 GPa) and tough α-β SiAlONs with an indentation fracture toughness of 5.5 MPa·m$^{1/2}$ [41].

Thanks to the excellent properties that (α+β)-SIAlONs have, they are used in the production of cutting tools. For example, Mandal et al. [55] designed (α+β)-SIAlON ceramics, which were produced in aqueous medium using multiple oxides as densifying additives. The sintered samples machined to cutting tool geometries were tested in turning and milling operations of cast iron and superalloy and the results were compared with some commercially available ceramic inserts. Hardnesses of the sintered (α+β)-SIAlONs are about 19 GPa, whereas hardness of most commercial Si_3N_4 is 15-16 GPa. The authors concluded that by a careful design of grain boundary chemistry (starting composition and sintering additives), (α+β)-SIAlONs ceramics can be produced and successfully used in machining operations.

In other work, Bitterlich et al. [56] made a first attempt to use particles such as SiC, WC, $MoSi_2$ and Ti(C,N) for (α+β)-SiAlON-composites for cutting tool applications. Although these composites did not produce satisfying results, they showed potential for further optimization.

The (α+β)-SiAlON-composites with different reinforcing particles (SiC, Ti(C30N70), $MoSi_2$, WC) were prepared by gas pressure sintering. Under the sintering conditions a strong interaction of $MoSi_2$ and WC with the matrix was observed, resulting in a change of the composition of the reinforcing phase and also of the (α+β)-SiAlON ratio. This strongly influenced the properties of the composites. The best wear behaviour

exhibited the material with 10 vol% SiC. The material reinforced with $MoSi_2$ showed a reasonable wear behaviour – despite its low fracture toughness and low hardness – indicating some special effects, which should be investigated in more detail.

3.4. SiAlON application in machining nickel-based alloys

Due to the physical and mechanical properties of SI-AlONs used as cutting tools, their use in the processing of nickel alloys is very widespread. Much research has been done to determine the effectiveness of sialons application compared to other ceramics. For instance, Krebs et al. [57] investigated the use of whiskers-reinforced ceramic tools and SiAlON in turning of alloy 625 clad on AISI 4130 steel by an automatic tungsten inert gas (TIG) cladding system. The results indicate the feasibility of the industrial application of the SiAlON inserts in rough turning of the alloy 625 clad, as well as the impossibility of using whiskers-reinforced ceramic tools (Al_2O_3+SiCw) in the same conditions. It was determined that considerably higher material removal rates can be achieved with SiAlON, instead of using conservative cutting parameters with coated cemented carbide tools. Tool wear pattern of the SiAlON inserts were similar for the different cutting conditions. Wear occurred on the flank face in formation of a relative uniform flank wear and high V-shaped notch wear. The highest flank and notch wear were observed for the lowest cutting speed (140 m/min), which induced the formation of burrs in the workpiece at the depth of cut. Adhesion occurred more intensively at this condition. The least flank and notch wear were achieved by using cutting speed of 160 m/min and feedrate of 0.25 mm/rev. Prolonged turning with worn tools resulted in microstructural alterations of the workpiece material and surface damages like cavities that may be associated with the carbide particles inside the machined surface.

Lima Fabio F. et al. [58] conducted a study on turning a nickel-based superalloy Inconel 751 using argon and oxygen atmospheres. Three groups of materials were used as cutting tools: SiAlON (Si_3N_4 + Al_2O_3), Whisker (Al_2O_3 + SiCw) and Mixed (Al_2O_3 + TiC). Experiments have shown that cutting speed, tool geometry and cutting fluid affect the type of wear and tool life. However, the best results have been achieved with SiAlON tools.

Zheng et al. [59] investigated the wear mechanisms of a Sialon ceramic tool in ultra-high-speed turning Inconel 718. The main wear mechanisms identified in the experimental part were adhesive and mechanical wear. SEM and EDS, during critical wear on the inserts edge, deposits in the form of separate elements Ni, Fe and Cr were found, contributing to a more active development of wear. The author also noted a serrated morphology shaving, indicating that thermal deformation during the cutting process.

Li et al. [60] in their work determined the optimal cutting speed when processing Inconel 718, at which there are no

diffusion phenomena that contribute to the formation of cuts on the back surface and craters on the front surface.

Nalbant et al. [61] studied the wear mechanisms of Si-AlON tools when machining a nickel alloy with plates having different geometric shapes (RNGN 120700 and SNGN 120712). Practice has shown that the predominant failures of square plates are crater wear along the front surface and mechanical wear along the rear surface, while for round plates the formation of notches and mechanical wear on the rear surface. The authors explain this by the fact that round inserts allow the use of different plunge angles, depending on the processing modes. This allows you to control piercing and notching.

Zheng et al. [62] proposed a new composition of SiAlON tools, strengthening it by introducing graded nano-α-Si_3N_4 into its composition. The experimental material made it possible to reduce the coefficient of friction and reduce the adhesive reactions. Mechanical tests showed that the introduction of α-Si_3N_4 made it possible to reduce microcracks on the working parts of the inserts, which made it possible to increase the cutting speed up to 300 m/min.

Shalaby et al. [63] used SiAlON ceramic tools in processing of aerospace superalloy Inconel 100 (IN100). The effect of cutting speed on chip formation in dry finish turning was investigated. It is noted in the work that a change in cutting speeds in a certain range leads to the formation of various lubricating and protective tribo-films that contribute to the elimination of the development of microcracks and defects.

4. Conclusions

The review showed that effective Nickel-Based HRSA treatment is a pressing issue. The most promising direction of development is the use of progressive methods of introducing alloying elements into the SiAlON and Si_3N_4 ceramic matrix. Due to their natural properties, traditional materials such as carbide, CBN, and PCD have functional limitations and low processing potential for Nickel-based alloys.

In the third section, SiAlON cutting tools were considered as a suitable material for machining a variety of difficult-to-cut materials, including nickel alloys, due to their special characteristics such as good fracture toughness, hardness (even at high temperatures) and resistance to sudden changes in temperature. In addition, this section provides a description of the various types of SiAlON ceramics such as α-SiAlON, β-SiAlON and their combinations (α + β). Examples of the use of sialons in the processing of nickel-based superalloys are given.

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