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A Review of Milling of Gamma Titanium Aluminides

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Abstract

Intermetallic titanium aluminide alloys are used in the high technology engineering field with the goal of achieving weight reduction in different components, exposed to corrosive environments and high temperatures in aeronautical and automotive industries. Despite their attractive properties such as low density, high strength, high stiffness and good corrosion, creep and oxidation resistance, the machinability of titanium aluminide alloys is difficult due to its high hardness, chemical reactivity, and low ductility. This article reviews the state of the art regarding the machinability of titanium aluminide alloys and focuses on the analysis of the milling process, namely the process parameters, surface integrity and cutting tools. The influence of titanium aluminides properties on the machinability is also discussed presenting some current trends and further needed research.

Author Keywords. Industrial Research, Mechanization, Technological Process, Milling, Gamma Titanium Aluminides, Surface Quality

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1. Introduction

Currently, in the aerospace and automotive industries, Gamma titanium aluminide alloys are presented as a better alternative in parts which are exposed to work temperatures around 800°C (Appel and Wagner 2001). These alloys are considered an interesting option to replace the nickel-based superalloys because of their enhanced physical and mechanical properties such as lower density, strength and stiffness, corrosion resistance, creep and oxidation resistance (Table 1). In the past, these attractive properties of Gamma TiAl were not fully exploited due to the difficulty in processing and machining these alloys at room temperature.

Property	Gamma-TiAl alloys	Nickel based Superalloys
Density (g/cm^3)	3.7 – 3.9	8.3
Young Modulus RT (GPa)	160 – 176	206
Yield Strength (MPa)	400-630	1000
Tensile Strength (MPa)	450 – 700	1200
Ductility at room Temperature (%)	1-3	15
Creep limit (°C)	1000	1090
Oxidation (°C)	900-1000	1090
Hardness (HV10)	285-350	320-390

Table 1: Summary of properties of Gamma TiAl and Nickel based superalloys (Kothari, Radhakrishnan, and Wereley 2012)

On the other hand, room temperature ductility, fracture toughness and fatigue crack growth are also complex characteristics on the processing of the titanium aluminides. Nonetheless, advances in manufacturing technologies, a better understanding of microstructure and deformation mechanisms, has led to their commercial use. This material has a particular interest in the production of rotating parts in gas turbine aero-engine for aeronautical industry and is also used to conrod, engine valves and turbine wheels of turbochargers for automotive engine applications. These applications, report that the reduction in weight compared to conventional nickel-based super alloys implies fuel saving, an increase in engine efficiency and consequently a reduction of CO_2 emission (Appel, Paul, and Oehring 2011).

The brittle nature, high chemical reactivity, high strength and relatively low heat conductivity strongly contribute to extra difficulties in the machining process of titanium aluminides. Nevertheless, these inconveniences pose challenges to the machining field technology players, such as cutting tool manufacturers and materials researchers.

Another challenge is that the manufacture of parts for aeronautical and automotive industries requires, generally, high dimensional accuracy and good surface integrity, being the machining process an essential procedure for reaching these requirements on accuracy and productivity (Zitoune, Krishnaraj, and Davim 2013).

Nowadays, in the titanium aluminides machining field, a lack of specific technical information such as cutting parameters, tool geometries, tools materials, coatings, cutting fluids, among others, slow down their commercial use and research. Most of the research in titanium aluminides machining is conducted using the existent information for titanium Ti-6Al-4V allow, which has been the most extensively studied alloy of the group of titanium alloys.

According to several researchers (Aust and Niemann 1999; Aspinwall, Dewes, and Mantle 2005; Beranoagirre, Olvera, and López de Lacalle 2012; Ge, Fu, and Xu 2007; Mantle and Aspinwall 2001; Weinert, Bergmann, and Kempmann 2006), low thermal conductivity, low elastic modulus, high strength and the brittle nature of titanium aluminides are the main factors for their poor machinability. These factors conduct to the rapid degradation of the machining tools, low material removal rate, and low surface quality of machined parts.

Some researchers have been dedicated to the development of titanium aluminides machinability, where optimization of the integrity surface(Mantle and Aspinwall 2001; Kolahdouz et al. 2015; Bentley, Mantle, and Aspinwall 1999; Priarone et al. 2016; Priarone, Rizzuti, Rotella, et al. 2012; Radkowski and Sep 2014), selection of cutting parameters (Aspinwall, Dewes, and Mantle 2005; Aust and Niemann 1999; Beranoagirre, Olvera, and López de Lacalle 2012; Bruhis, Sebring, and Noland 2008; Priarone, Rizzuti, Settineri, et al. 2012; Weinert, Bergmann, and Kempmann 2006), tool wear (Vargas Pérez 2005; Priarone et al. 2016; Priarone, Rizzuti, Rotella, et al. 2012; Barakchi Fard and Feng 2009; Priarone, Rizzuti, Settineri, et al. 2012), machining environment (Priarone et al. 2011; Aspinwall et al. 2013; Barakchi Fard and Feng 2009), are the main topics focus of research.

The machining process involves many variables as can be seen in Figure 1 (ASM International 1989), and so a comprehensive review would be complex. This article is focused on the milling process, with especial attention to the cutting parameters, surface roughness, cutting environment and the influences of the material properties on machinability are also highlighted.

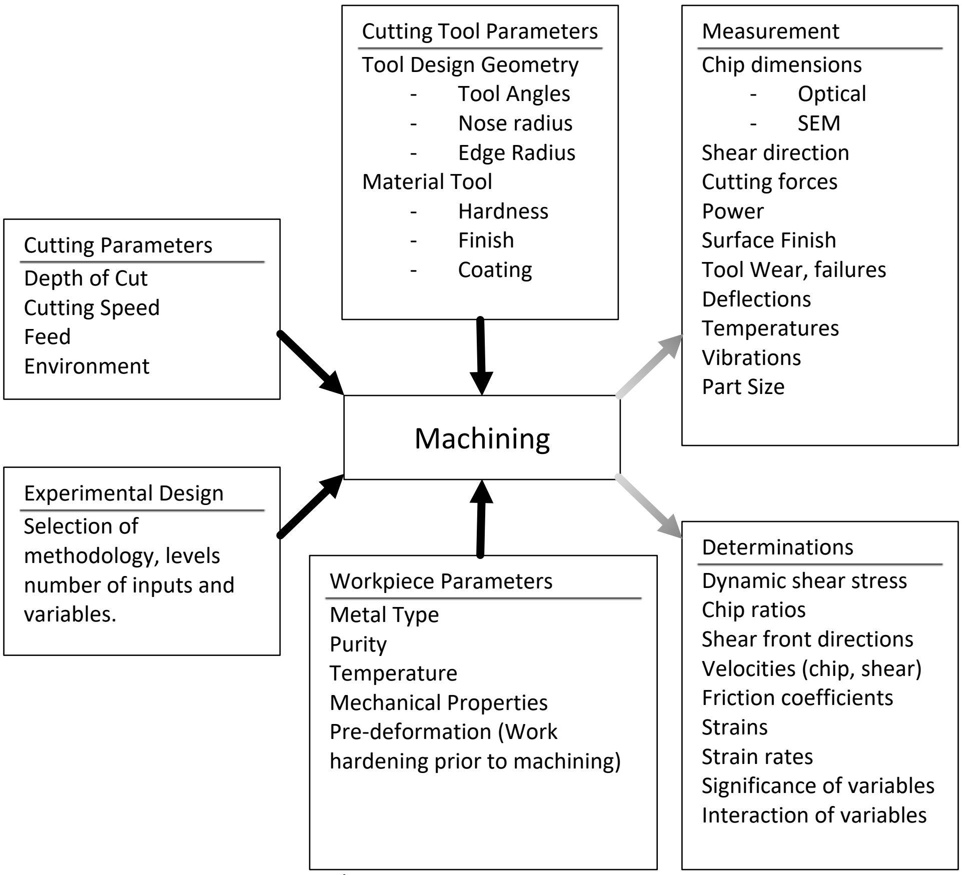


Figure 1: Inputs/outputs relationship in machining process (adaptated of ASM International 1989)

2. Gamma TiAl properties and Machining

Gamma Titanium Aluminides present low machinability due to their low thermal conductivity, high reactivity, low ductility, high hardness and strength and work hardening feature.

The thermal conductivity of Ti-based intermetallic alloys (about 22 W/mK) as Gamma TiAl typically contain 45 % Al, is three times higher tthan in titanium alloys (about 7.3 W/mK) and markedly lower than aluminum alloys (about 170-200 W/mK at 0°C) (Appel, Paul, and Oehring 2011), but the induced wear or their adverse impact on workpiece integrity by thermal effects in titanium aluminides are not less significant than in classical titanium alloys such as Ti-6Al-4V.

Considering the properties shown in Table 1, especially tensile strength, yield strength and hardness, one can understand that the Gamma-TiAl alloys require less machining power than the Ni-based superalloys (Aspinwall et al. 2013), but due to their low ductility (typically quoted between 1-3%), generally titanium aluminide show poor workpiece integrity.

Conventional machining of Gamma-TiAl is significantly more difficult than with standard titanium alloys, in terms of tool wear, tool life, cutting forces, temperature, productivity and workpiece surface integrity. Furthermore, a lack of correct machining parameters, specific tool geometries and other operation technological aspects, affect the parts surface integrity that tend to exhibit microcrack formation, deformed surface drag and increased surface micro hardness (see Table 2).

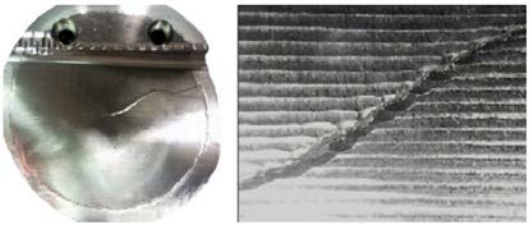
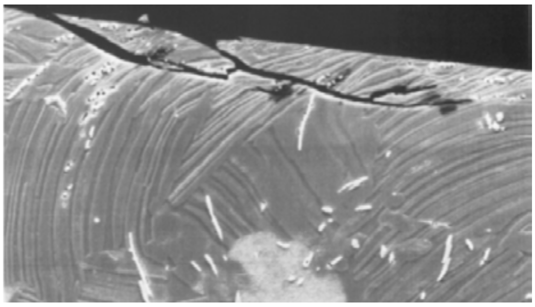
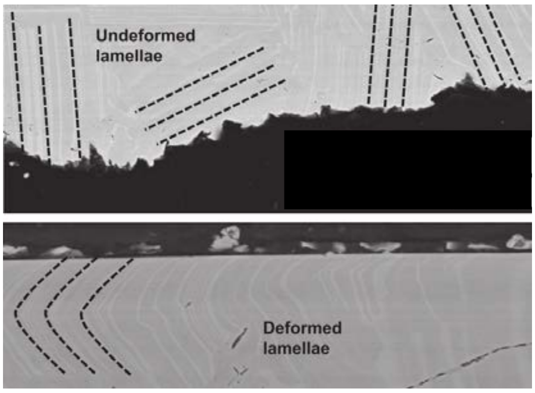
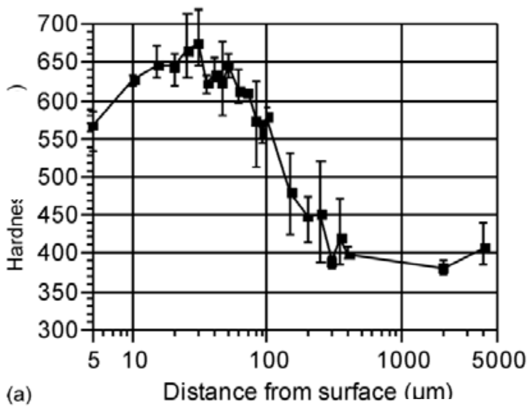
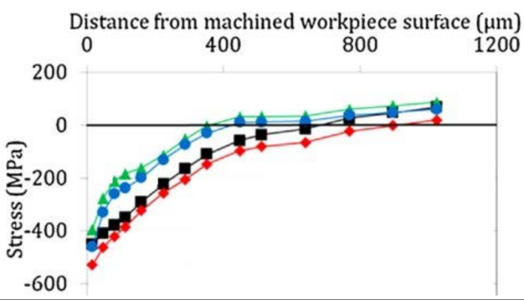
Machined Surface Integrity Defects	Details	Ref.
	Blade made in Gamma-TiAl (MoCuSi) with a deformed surface crack that appeared during machining because of the material brittle behavior and excesive cutting speed.	(Beranoagirre, Olvera, and López de Lacalle 2012)
	Machined workpiece in Gamma Titanium Alumindes showing surface cracks caused by lower ductility, leading to failure of the part by fatigue crack propagation.	(Mantle and Aspinwall 2000)
	Section of a machined surface, where surface drag can be evidenced by the lamellae deformation. This phenomenon indicates strain at the high temperatures generated during the machining process	(Klocke et al. 2013)
	The increasing of sub-surface hardness indicates susceptibility of material to strain hardening, reducing even further the poor ductility at the surface	(Mantle and Aspinwall 2001)
	High cutting temperatures cause a decrease in yield strength; it is a typical result in tensile residual stresses, due to the thermal expansion constrain of the workpiece, leading to plastic compression on the heated area.	(Hood et al. 2014)

Table 2: Summary of surface integrity defects on gamma TiAl parts

3. Milling of Gamma TiAl

Research reports on Milling of titanium aluminides are focused on the analysis and improvement of the machined surface integrity. These studies involve several considerations such us: surface finish, absence of cracks, evidence of thermal damage and adverse residual stress. Surface finish is by far the most important for machining operations, being the main requirement in the more common applications of Gamma TiAl alloys (automotive and aeronautical fields). The surface integrity researches are conducted assessing a combination of different values of cutting parameters. Machining tests are carried out with cutting speed values from 20 m/min (Aust and Niemann 1999) to 600 m/min (Kolahdouz et al. 2015), feed rates from 0.005 m/min (Kolahdouz et al. 2015) to 0.12 m/min (Aspinwall et al. 2013) and depth of cut from 0.1 mm (Kolahdouz et al. 2015) to 5 mm (Aust and Niemann 1999). Table 3 provides some cutting parameters studied on optimization of surface roughness for machining improvement.

On the other hand, cutting tools designed for machining of titanium alloys (commonly small diameter radius end and ball end milling cutters) have been tested. Furthermore machining research (Aspinwall et al. 2013; Barakchi Fard and Feng 2009; Vargas Pérez 2005; Priarone et al. 2016) shows that only cemented carbide C/W or harder cutting materials like CBN (cubic boron nitride) and PCD (Polycrystalline Diamond) can be used because of the high hardness and brittleness as well as the high strength of this material. The data, obtained from Taguchi methodology, normally cover assessment of tool materials, coatings, operating modes and parameters, fluid application, tool wear and workpiece surface roughness and integrity.

In the studies developed for the milling of titanium aluminates, interesting information is presented, where it is observed that the values of surface roughness obtained are between 0.8-0.155 µm. These results are achieved using common tools with TiAlN coatings to machine titanium based alloys (alpha, beta and alpha + beta) under different cutting environments.

On the other hand, the limited information that is available about the machining of titanium aluminides opens a new and interesting research area where it is still necessary to determine the influences of the tool properties such as materials, coatings and geometries, and their influence on the characteristics of the workpiece (surface integrity and roughness). Furthermore, as in other materials, it is also important to define the optimum cutting parameters in the production of parts for the machining of gamma TiAl alloys.

Ref.	Material	Tool		Machining Parameters				Surface Roughness (µm)
	Specification	Type	Material	Cutting Speed m/min	Feed (mm/tooth)	Axial Depth (mm)	Environment	
(Aust and Niemann 1999)	TiAl primary Casting	End Mill	Carbide K10-K20	17 20	0.01 0.04	1-5	wet (Emulsion 1:15) to 1.3lt/min	2.95 0.8
(Ge, Fu, and Xu 2007)	Ti-48Al-2Cr-2Nb	End Mill	Solid Carbide (TiAlN)	120 240	0.08	5	Dry	0.198 0.176
(Beranoagirre, Olvera, and López de Lacalle 2012)	Ti-45Al-(5-10)Nb-(0,2-0,4)C and Ti-(43-46)Al-(1-2)Mo-(0,2)Si-Cu	End Mill	Solid Carbide (TiAlN)	60 70	0.06	1	Wet (Emulsion FU 70 W Rhenus pH 7.7-8.8) 6lt/min	0.51 0.31
(Hood et al. 2013)	and Ti-45Al-2Mn-2Nb+0.8% Vol TiB2XD	Ball nose end mill	Solid Carbide (TiAlN PVD)	160 250	0.06	0.25	Dry	0.6 0.3
(Settineri et al. 2014)	Ti-48Al-2Cr-2Nb, Ti-45Al-2Mn-2Nb+0.8% Vol TiB2XD, Ti-43,5Al-4Nb-1Mo-0.1B	Toroidal end mill	Solid Carbide (TiAlN PVD)	90	0.1	0.3	6% Emulsion to 6 bar	1.7 0.5
(Kolahdouz et al. 2015)	Ti-48Al-2Cr-2Nb-1B (%at)	End Mill	Solid Carbide (TiAlN-PVD microcoating)	600 300	0.005	0.1	Dry and MQL 50ml/h at 50 mm from the tool tip	0.170 0.155

Table 3: Summary of cutting parameters studied on optimization of surface roughness for machining improvement

4. Conclusions

The properties of titanium aluminides such as high strength at elevated temperature produced during machining, high elastic modulus and chemical reactivity, thermal conductivity and low ductility have an adverse effect on the machinability of these intermetallic alloys. The published research agrees that the latter two are the most degrading factors.

Most of the research focuses on the adverse influence of low ductility and strength at high temperature, that leads to a lower surface integrity, sub-surface micro hardening, higher instability of the machining process and the fast wear of tool cutting edge.

Research on machining gamma-TiAl alloys started two decades ago, and has been contributing to an increase understanding of the microstructure, deformation and the relationships between these features and the cutting parameters on machining. Although the available information, currently there is still a lack of knowledge about the right (optimal) machining parameters for this materials, and besides there are also few studies on quantification of chemical reactivity between titanium aluminide and tool material, or the relationship between workpiece hardening and cutting parameters, tool geometry or cutting fluids.

Most of the investigation carried out on the machinability of gamma TiAl alloys is based on different cutting conditions, which makes it difficult to be compared, and be implemented in practical cases of producing optimized parts.

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