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SURFACE QUALITY OF A MILLED GAMMA TITANIUM ALUMINIDE FOR AERONAUTICAL APPLICATIONS

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Abstract
Gamma titanium aluminides are an interesting alternative for nickel, iron or cobalt matrix superalloys. Due to the advantageous strength properties at high temperatures they can successfully replace superalloys in applications such as high pressure compressor blades, low pressure turbine blades, high pressure compressor case, low pressure turbine case. Milling is one of the processes that can be applied in the forming elements made from this type of alloys for the aviation industry. Research included the selection of tool, the process kinematics and the range of milling gamma titanium aluminide (Ti-45Al-5Nb-0.2B-0.2C) process parameters were carried out. Milling can be an effective method of forming of elements made of gamma TiAL in the range of processing parameters: v_c = 20-70 m/min, a_p = 0.3–0.7 mm, f_z = 0.1–0.45 mm/tooth. In the tests carried out the best results were obtained using a R300-016A20L-08L milling cutter, S30T tool coating and in-cut milling.

Keywords
Gamma titanium aluminide, milling, surface roughness.

Introduction

Nowadays, nickel, iron or cobalt matrix superalloys (Inconel, Waspalloy, Rene) are commonly used in aerospace for elements operating at high temperature (high pressure compressor blades, low pressure turbine blades, high pressure compressor case and low pressure turbine case). A significant disadvantage from the aeronautical applications point of view, is their high density (8–8.5 g/cm^3) in comparison to other construction materials used in the aviation that reached the upper limit of the operating temperature (approximately 90% of the melting point) what limits further improve the performance of turbine engines.

An interesting alternative for these materials are gamma titanium aluminides. Thanks to the advantageous strength properties at high temperatures (650–850°C) can successfully replace superalloys in applications such as high pressure compressor blades, low pressure turbine blades, high pressure compressor case and low pressure turbine case. Gamma titanium aluminides show high resistance to oxidation and corrosion, good thermal stability due to high melting point and creep resistance.

Development works on gamma titanium aluminides were initiated in the mid-twentieth century [1]. The material became interesting for science and industry. This was due to excellent properties of the alloy at raised temperature. For contemporary TiAl alloys containing 35–44.5% Al (eg. Ti36Al), the temperature attained 550°C. At the beginning of the XXI century, alloys with a high content of niobium were worked out. The permissible operating temperature reached 850°C. Marked as γ-TNB are the third generation of the TiAl alloys. The chemical constitution is characterized by a constant content of aluminum – 45%, niobium – 5–10% and additions of carbon and boron < 1%. Due to the high content of niobium third generation alloys exceed the other alloys used for components in the hot section of the engine. The high strength of these alloys [1, 2], excellent creep and oxidation resistance at temperatures up to 850°C, make them as an alternative to the currently used nickel and titanium superalloys. TiAl based alloys are an attractive material for applications in aircraft constructions, both because of their characteristics and potential economic benefits. However, there are essential limitations that affect the possibility and the validity of using this material in the production. Technological limitations are one of the most important. Due to the big difficulty in forming and the tendency of reacting with other elements (impurities in the process) only a few and relatively expensive methods of processing can be applied in forming of the elements made of gamma titanium aluminides:

- isothermal forging,
- powder metallurgy,
- casting,
- machining.

The above mentioned limitations result in a very high production cost of gamma titanium aluminides, which effectively inhibits the application of this material on an industrial scale [2, 3]. Machining is one of the main methods of this material forming in the final stages of aircraft engine components production. During processes such as milling, turning, drilling, grinding, final form of parts, which must meet restrictive quality requirements are received. Machining of titanium alloys is much more difficult than processing other materials applied in the aerospace or automotive industry. The main reason for this is the fact that titanium alloys are characterized by a low coefficient of thermal conductivity. As a result, these alloys exhibit good resistance to high temperatures. Unfortunately, low coefficient of thermal conductivity results also in heat dissipation decrease and even its concentration on the cutting edge of tool. Temperature increases up to 1100°C, causing rapid wear of the tool and its deformation, as well as can lead to ignition. Another onerous feature of titanium alloys is the high chemical reactivity with cutting tools materials. The result is a build up of workpiece material on the rake face of the cutting blade and, consequently, chipping blade [4–11].

These conditions justify making the research work aiming at the selection of process parameters in order to fulfill the requirements of the aviation industry. The aim of the paper is to present the results of preliminary research focused on the selection of tools and kinematics and range of milling gamma titanium aluminide process parameters. Milling is one of the processes that can be applied in the forming elements made from this type of alloys for the aviation industry [10, 12].

Test methodology

Research included the selection of tool, the process kinematics and the range of milling gamma titanium aluminide (Ti-45Al-5Nb-0.2B–0.2C) process parameters were carried out. Research was conducted with the parameters to ensure adequate choices. Flat surfaces, which were face of the rod with a diameter of 70 mm were milled. Machining of the samples was performed on a five axis milling center HAAS VF-2. The basic criterion for the assessment of machining effects was to obtain surface roughness characterized by Ra parameter. The roughness was measured in a direction perpendicular to the feed motion of the tool using a white light interferometer CCI Lite. Industrial requirements for the process assume the achievement of the Ra parameter less than 0.8 µm. Macroscopic and microscopic metallographic evaluation were also carried out using appropriately stereoscopic microscope Nikon SMZ 1000 and microscope Nikon Epiphot 300. Moreover the fluorescent penetrant inspection was also carried out. Metallographic evaluation and fluorescent penetrant inspection aimed to detect cracks or other surface defects.

Results and analysis

Selection of the machining tool

Seven tools were selected for preliminary research. The criterion for selection was the value of the tool blade wear, calculated as the ratio of the blade wear $V_{B\,\max}$ to the volume of material removed V. Initial machining parameters were assumed as: $v_c =$ 45 m/min, $a_p = 0.5$ mm, $f_z = 0.25$ mm. In the case of obtaining positive results machining was conducted at increased machining velocity $v_c = 85$ m/min. When the initial parameters were assumed, four of tools showed extremely rapid wear of the cutting blade. Tools qualified to next phase of the research (Fig. 1) showed significantly greater life of cutting edge both for initial parameters and for increased cutting speed $v_c = 85$ m/min (Fig. 2).

1) Milling cutter AJX06R162SA16S
2) Milling cutter R300-016A20L-08L
3) Milling cutter R390 E45 D16-W25

Fig. 1. Milling cutters qualified to next phase of the research.

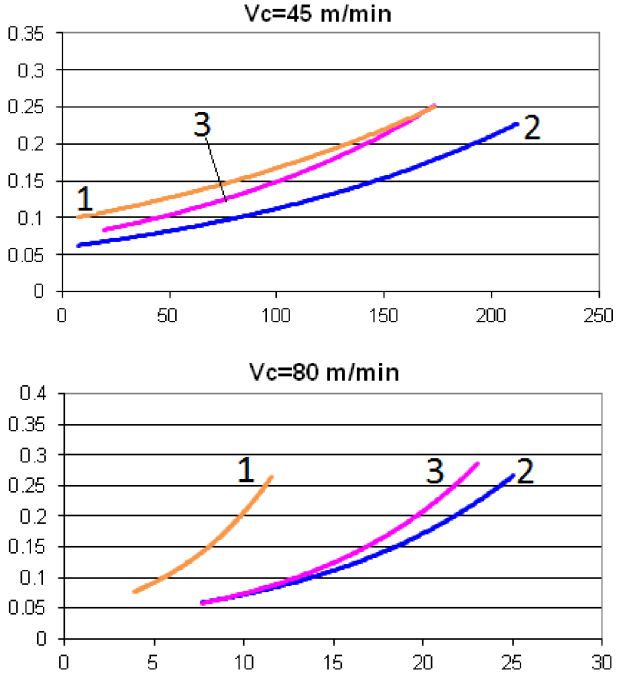

Fig. 2. Cutting blade wear for machining parameters $v_c = 45$ m/min and $v_c = 80$ m/min, $a_p = 0.5$ mm, $f_z = 0.25$ mm.

Tool number 2 showed the best life of the cutting blade and was chosen for next stage of research of milling γ-TiAl alloy.

Selection of the range of machining parameters

Selection of milling parameters range was made on the basis of their influence on surface topography. Three machining parameters were assumed as variables: machining velocity v_c [m/min], feed per tooth f_z [mm/tooth] and depth of cut a_p [mm]. Each of parameters were assumed for five levels of variability (Table 1).

Table 1
Machining parameters.

v_c [m/min]	20	a_p [mm]	0.3	f_z [mm/tooth]	0.10
	30		0.4		0.15
	45		0.5		0.25
	60		0.6		0.35
	70		0.7		0.45

The obtained results are presented in Table 2.

Table 2
The results of surface roughness measurement – machining parameters.

Test No	v_c [m/min]	a_p [mm]	f_z [mm/tooth]	R_a [µm]			
				a	b	c	mean
1	20	0.5	0.25	0.523	0.626	0.566	0.572
2	30	0.5	0.25	0.505	0.594	0.589	0.563
3	45	0.5	0.25	0.492	0.474	0.530	0.499
4	60	0.5	0.25	0.669	0.739	0.756	**0.721**
5	70	0.5	0.25	0.585	0.537	0.498	0.540
6	45	0.3	0.25	0.366	0.342	0.361	0.356
7	45	0.4	0.25	0.441	0.379	0.387	0.402
8	45	0.5	0.25	0.492	0.474	0.530	0.499
9	45	0.6	0.25	0.404	0.390	0.427	0.407
10	45	0.7	0.25	0.469	0.465	0.437	0.457
11	45	0.5	0.1	0.363	0.325	0.414	0.367
12	45	0.5	0.15	0.325	0.316	0.352	**0.331**
13	45	0.5	0.25	0.492	0.474	0.530	0.499
14	45	0.5	0.35	0.412	0.421	0.412	0.415
15	45	0.5	0.45	0.517	0.627	0.541	0.562

Analysis of the results shows that the assumed range of milling process parameters (Table 2) ensures fulfilling the criterion of acceptability assuming the surface roughness parameter $R_a \leq 0.8$ µm. Carrying out machining with the largest of the asumed parameters allows to obtain surfaces, for which the parameter R_a is similar to the accepted upper limit of 0.8 µm.

The selection of the cutting tool coating was made between three offered coatings for milling cutter R300-016A20L-08L. Avaiable coatings are:

- 1025 – PVD coating for superalloys milling; exhibits high resistance for accretion forming and plastic strain,
- 30 T – PVD coating characterized by sharp cutting edge with high resistance for fatique and microcracks,
- 40 T – CVD coating allows to obtain good results in the case of difficult cutting conditions (vibrations, etc.).

The obtained results are presented in Table 3.

Table 3
The results of surface roughness measurements – cutting edge coatings.

Test No	Plate code	Parameters					R_a			
		v_c [m/min]	a_p [mm]	f_z [mm/tooth]	F_{obr} [mm/rev]	S [rev/min]	a	b	c	mean
16	S30T	20	0.3	0.1	0.2	398	0.174	0.193	0.187	**0.185**
17	S30T	70	0.3	0.1	0.2	1393	0.191	0.235	0.205	0.210
18	S30T	70	0.3	0.45	0.9	1393	0.836	0.944	1.150	0.977
19	S30T	20	0.3	0.45	0.9	398	0.838	0.859	0.866	0.854
20	S30T	20	0.7	0.1	0.2	398	0.193	0.391	0.448	0.344
21	S30T	70	0.7	0.1	0.2	1393	0.307	0.344	0.373	0.341
22	S30T	70	0.7	0.45	0.9	1393	0.718	0.813	0.756	0.762
23	S30T	20	0.7	0.45	0.9	398	1.380	1.030	1.060	**1.157**
24	S40T	20	0.3	0.1	0.2	398	0.234	0.556	0.428	0.406
25	S40T	70	0.3	0.1	0.2	1393	0.487	0.600	0.582	0.556
26	S40T	70	0.3	0.45	0.9	1393	0.735	0.676	0.721	0.711
27	S40T	20	0.3	0.45	0.9	398	0.646	0.840	0.976	0.821
28	S40T	20	0.7	0.1	0.23	98	0.406	0.342	0.452	0.400
29	S40T	70	0.7	0.1	0.2	1393	0.216	0.235	0.244	**0.232**
30	S40T	70	0.7	0.45	0.9	1393	0.614	0.751	1.580	0.982
31	S40T	20	0.7	0.45	0.9	398	0.683	1.040	2.080	**1.268**
32	1025	20	0.3	0.1	0.2	398	0.460	0.367	0.451	0.426
33	1025	70	0.3	0.1	0.2	1393	0.345	0.281	0.290	0.305
34	1025	70	0.3	0.45	0.9	1393	0.682	0.641	0.682	0.668
35	1025	20	0.3	0.45	0.9	398	0.544	0.614	0.660	0.606
36	1025	20	0.7	0.1	0.2	398	0.440	0.330	0.357	0.376
37	1025	70	0.7	0.1	0.2	1393	0.314	0.324	0.271	**0.303**
38	1025	70	0.7	0.45	0.9	1393	0.730	0.655	0.554	0.646
39	1025	20	0.7	0.45	0.9	398	0.867	1.270	1.230	**1.122**

Results included in Table 3 show clearly that surfaces machined by applying the PVD coated tool codenamed S30T have the lowest parameter R_a of all the tested surfaces. It is a coating designed for half-finishing, ensure the possibility of application higher cutting speeds and longer life of a cutting blade. The application S30T coating ensure to obtain surface roughness in the range of 0.185–1.157 µm. In turn, the application of S40T coating allowed to obtain parameter Ra in the range of 0.232–1.268 µm, whereas surfaces machined using CVD coated tool (1025) were characterized by roughness in the range of 0.303–1.122 µm. Based on obtained results S30T coating was qualified for further investigations.

Selection of process kinematics

For selected tools and cutting tool coating in the previous stages of the research, investigations aiming at the selection of the process kinematics were realized. Scheme of investigations is presented in Fig. 3.

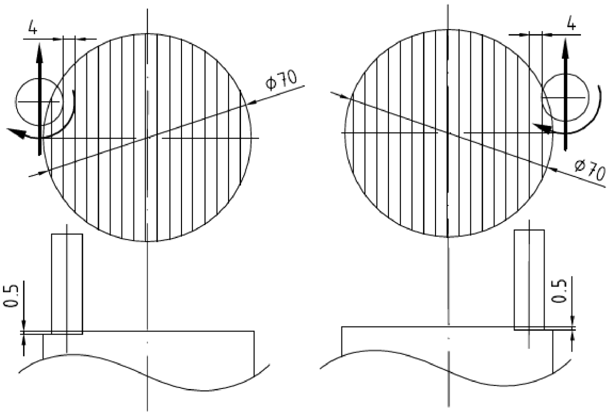

Fig. 3. Milling kinematics.

A series of experiments using the in-cut milling (Fig. 3a) and out-cut milling (Fig. 3b) were carried out. Surface roughness test results are presented in Table 4.

Table 4
The results of surface roughness measurements – process kinematics.

Test No	Plate code	Parameters					R_a			
		v_c [m/min]	a_p [mm]	f_z [mm/tooth]	F_{obr} [mm/rev]	S [rev/min]	a	b	c	mean
In-cut milling										
40	30T	20	0.3	0.1	0.2	398	0.282	0.214	0.191	0.229
41	30T	70	0.3	0.1	0.2	1393	0.300	0.214	0.236	0.250
42	30T	70	0.3	0.45	0.9	1393	0.552	0.491	0.481	0.508
43	30T	20	0.3	0.45	0.9	398	0.628	0.647	0.613	**0.629**
44	30T	20	0.7	0.1	0.2	398	0.298	0.256	0.274	0.276
45	30T	70	0.7	0.1	0.2	1393	0.237	0.204	0.222	**0.221**
46	30T	70	0.7	0.45	0.9	1393	0.526	0.435	0.543	0.501
47	30T	20	0.7	0.45	0.9	398	0.505	0.609	0.636	0.583
Out-cut milling										
56	30T	20	0.3	0.1	0.2	398	0.261	0.278	0.314	0.284
57	30T	70	0.3	0.1	0.2	1393	0.292	0.273	0.275	**0.280**
58	30T	70	0.3	0.45	0.9	1393	0.893	0.634	0.769	0.765
59	30T	20	0.3	0.45	0.9	398	0.613	0.570	0.570	0.584
60	30T	20	0.7	0.1	0.2	398	0.264	0.284	0.317	0.288
61	30T	70	0.7	0.1	0.2	1393	0.388	0.370	0.328	0.362
62	30T	70	0.7	0.45	0.9	1393	0.964	0.940	2.350	**1.418**
63	30T	20	0.7	0.45	0.9	398	0.747	0.692	0.744	0.728

Analysis of the obtained results clearly indicates that the favorable kinematics of the process is in-cut milling. The surface roughness range 0.221–0.629 µm was obtained in this case. When out-cut milling, this range was 0.280–1.418 µm.

Metallographic evaluation and fluorescent penetrant inspection

The metallographic evaluation and fluorescent penetrant inspection showed no surface defects. Examples of the results of metallographic evaluation and fluorescent penetrant inspection are shown in Fig. 4.

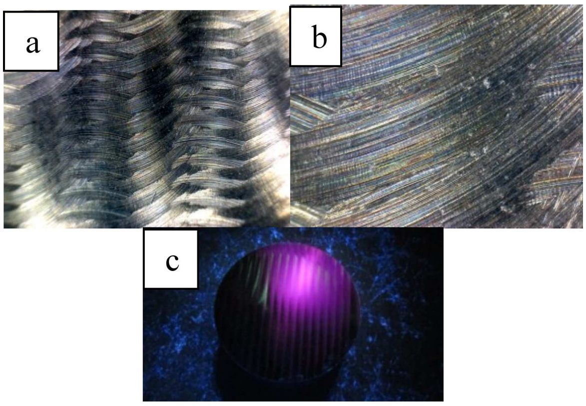

Fig. 4. Results of metallographic evaluation (a, b) and fluorescent penetrant inspection (c).

Results in Fig. 4 showed a typical surface after milling and lack of surface defects. This confirms the possibility of efficient milling of gamma titanium aluminide using the selected tool, kinematics of the process and machining parameters.

Conclusions

1. An interesting alternative for nickel, iron or cobalt matrix superalloys are gamma titanium aluminides. Thanks to the advantageous strength properties at high temperatures they can successfully replace superalloys in applications such as high pressure compressor blades, low pressure turbine blades, high pressure compressor case and low pressure turbine case.
2. Milling can be an effective method of forming of elements made of gamma TiAL in the range of processing parameters: $v_c = 20–70$ m/min, $a_p = 0.3–0.7$ mm, $f_z = 0.1–0.45$ mm/tooth.
3. The best results were obtained using a R300-016A20L-08L milling cutter, S30T tool coating and in-cut milling in the performed tests.

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