Measurement and analysis of variations in cutting resistance forces occurring during the milling of titanium alloy with an intermetallic matrix γ-TiAl using a monolithic ceramic end mill

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Abstract
This paper presents the experimental setup and selected results of milling tests on a titanium alloy with an intermetallic matrix γ-TiAl alloy using a monolithic ceramic end mill. The focus was on measuring cutting forces and their variation at different values of cutting speed v_c, related to tool rotation, and tool feed rate *f* per tooth along the cutting path. Signals associated with time-varying values of the resistive component of the total cutting force were subjected to spectral analysis using the Fast Fourier Transform (FFT). It was observed that the tool feed rate *f* has little effect on the values of the dominant frequency of cutting force variations. It was also noted that as the cutting speed v_c increases, the value of the dominant of the resistive component of the total cutting force also increases significantly. The dominant frequency was determined by computing and analysing the Power Spectral Density (PSD) of the signals from the forces measured by the force gauge. The typical wear pattern of the ceramic tool used in the study was also demonstrated. The results of the study indicate that it is possible to deliberately influence the resistive component of the total cutting force and process stability through process control parameters.

Keywords: titanium alloy, intermetallic matrix γ-TiAl, monolithic ceramic end mill, Fast Fourier Transform, Power Spectral Density, tool wear

1. Introduction

The excellent mechanical properties of titanium alloy with an intermetallic matrix γ-TiAl make it a highly effective aerospace material, particularly for use in propulsion systems, especially in Low-Pressure Turbines [1, 2]. This material has very good specific strength, high oxidation and creep resistance, and it is expected to help reduce the aero-engine weight by 20%–30% [3, 4]. However, its inherent brittleness and high specific strength cause machinability difficulties of various physical nature.

The machinability of titanium alloys with an intermetallic matrix γ-TiAl is lower than that of conventional alloys, which are already difficult to machine, due to their low plasticity, brittleness at room temperature, high chemical reactivity, and hardness. The low thermal conductivity of these alloys (approx. 15 W/m²K) [5] results in poor heat dissipation from the cutting zone, the surfaces of the cutting tools, and the workpiece. During machining there is a significant increase in temperature in the cutting zone. As a result of the high temperature acting on the surface layer, its phase composition and microstructure morphology change, leading to material hardening and the formation of shape defects in the workpiece [1, 2, 6-8].

The poor machinability of gamma aluminide titanium alloys, compared to other titanium alloys – following their high hardness, brittleness, high chemical reactivity, and low thermal conductivity – leads, among other things, to reduced machining efficiency. To counteract this, a monolithic ceramic end mill can be used in for milling these materials because it allows for machining along much longer cutting edges than is the case with end mills equipped with cutting inserts. Moreover, ceramic tools are characterised by high hardness at elevated temperatures, better chemical stability, and greater resistance to oxidation compared to cemented carbides. However, they have lower resistance to dynamic loads, and therefore their use requires machine tools with high rigidity and stability, as well as greater power to enable high-speed machining. The dominant wear mechanism is abrasive wear [1, 2, 8]. These issues have received little attention in the literature, even though these issues are important. Therefore, this paper presents selected results from research on the milling process of alloy samples using a milling cutter. The study focused particularly on the variability of cutting resistance and tool wear.

Section 2 presents the research methodology, describes the experimental setup, and outlines the conditions under which the experiments were conducted. Section 3 presents and briefly discusses the results of the study. Section 4 contains selected conclusions drawn from the study.

2. Research methodology and the experimental setup

2.1. Test bench and conditions for conducting experiments and measurements of the components of total cutting force

Research on the milling process of a titanium alloy with an intermetallic phase matrix γ-TiAl with a chemical composition of Al-45 wt%, Nb-5 wt%, B-0.2 wt%, C-0.2 wt%, Ti-49.6 wt%, and a hardness of approx. 40 HRC were conducted using a DMU 80P duoBlock 5-axis machining center (Fig. 1). The test bench for measuring variations in cutting forces consisted of the machining center, force gauge Kistler 9257B, signal amplifier, Data Acquisition Device (DAQ) and laptops for data acquisition and analysis.

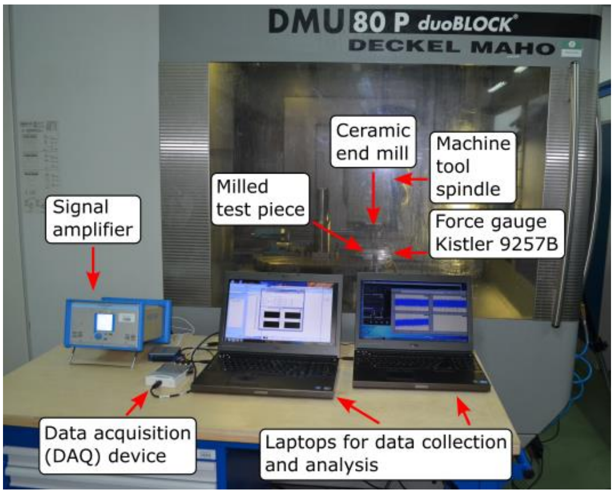

Figure 1. View of a test bench for measuring variations in cutting forces during the milling of a gamma aluminide titanium alloy γ-TiAl with a monolithic ceramic milling cutter

Side milling was adopted as the main operation. The setup in the machining area, including the test specimen, the force gauge, and the milling cutter, is shown in Fig. 2, along with the local coordinate system associated with the force gauge and the workpiece.

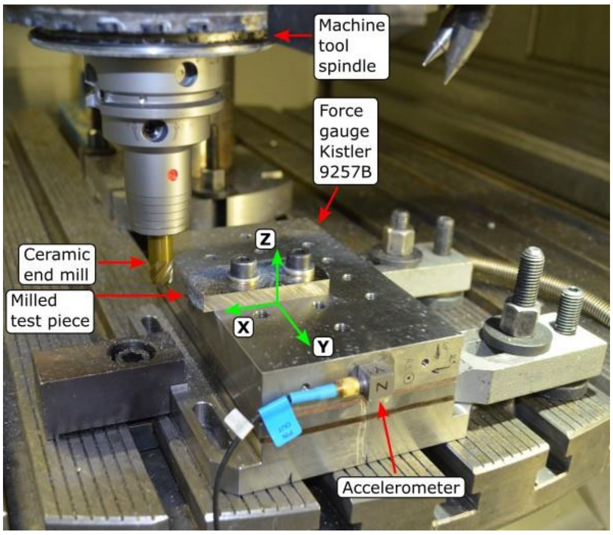

Figure 2. View of the work area of the test bench, shown in Fig. 1, illustrating the mounting of the applied force gauge Kistler 9257B, the workpiece made of a gamma aluminide titanium alloy γ-TiAl, and the side surface of the workpiece being machined with a monolithic ceramic milling cutter, as well as the orientation of the local coordinate system XYZ used in measuring generated variations in cutting forces

A monolithic ceramic end mill was used: diameter d = 12 mm, number of cutting edges z = 6, corner radius r_ε = 1.5 mm, helix angle λ = 40° with regular pitch. The tool material was SiAlON KYS40 ceramic (Fig. 2). The following cutting parameters were adopted: cutting speed $v_c \in \{350, 450, 550\}$ m/min, feed rate per tooth $f \in \{0.03, 0.04, 0.05, 0.06, 0.07\}$ mm/tooth, axial depth of cut a_p = 7 mm and radial depth of cut a_e = 0.2 mm.

During machining process, the components Fx, Fy and Fz of the total cutting force F were measured using a Kistler 9257B piezoelectric dynamometer (Fig. 2) with a measurement range of ±5 kN, a Kistler 5070 load amplifier, and a 16-bit Ni9215 analog-to-digital converter. A sampling frequency of f_s = 10 kHz was used.

The surface roughness parameters of the workpiece were measured using a Mahr Perthometer 2 profilometer. The microstructure, on the other hand, was examined using an Epiphot metallographic microscope. Two surface roughness parameters, Ra and Rz, have been measured and determined as the most commonly used in industrial practice. The first of these, Ra, is the Roughness Average parameter representing the arithmetic average of the absolute heights of microscopic peaks and valleys along a surface. It measures general surface smoothness. The second determined surface texture parameter, Rz, commonly referred to as Average Peak-to-Valley Roughness, characterises the average distance between the five highest peaks and the five deepest valleys across a surface and therefore provides a better description than Ra of local surface defects, such as microcracks, scratches, etc. [9].

2.2. The methodology used for processing measurement signals representing the components of the total cutting force

All components of the total cutting force were measured. The resistive component of the total cutting force, i.e. the normal force component Fx in accordance with the local coordinate system (Fig. 2), was subjected to detailed analysis, because preliminary studies had shown that it has a significant impact on tool geometry deformation, tool wear and, consequently, on product accuracy and its surface texture.

The signals were transformed and analysed using the Fast Fourier Transform (FFT) [10] in order to compute the specific frequencies present in the measured signal. The Power Spectral Density (PSD) was also applied to the measured signals to determine how the power of each signal is distributed over frequency, normalized by bandwidth.

In order to smooth discontinuities at the beginning and end of the sampled signal the Hann window [10] was applied:

$$g(n) = 0.5 - 0.5\cos\left(\frac{2\pi n}{M-1}\right), 0 \leq n \leq M-1$$

where n and M denote point number and the number of points in the output window, respectively.

The Power Spectral Density (PSD) was computed with a method developed by Welch [11]. The PSD function of the measured signal was estimated using this method by dividing the data into overlapping signal ranges and computing a modified periodogram for each range. At the next stage the calculated previously periodograms were averaged. The Python 3.13 programming environment, along with its libraries, in particular SciPy [12], Matplotlib [13] and seaborn [14], was used for computations and to visualize the results.

3. Research findings and discussion of the results

3.1. The total cutting force and machined surface texture

Performed studies of the milling process of a titanium alloy with a γ-TiAl intermetallic phase matrix using monolithic ceramic tools have shown that the lowest measured total cutting force, F = 190 N, occurs at the cutting speed v_c = 550 m/min and feed rate per tooth f = 0.03 mm/tooth. The biggest value of the total cutting force, F = 640 N, occurs at the cutting speed v_c = 350 m/min and the feed rate per tooth f = 0.07 mm/tooth (Fig. 3). Increasing the cutting speed, at a given feed rate that is linked to the tool's rotational speed, can lead to more effective plastic deformation of the workpiece material in the machining zone. Furthermore, increasing the cutting speed improves the evacuation of chips generated during cutting from the machining zone. This may be the reason for the decrease in total cutting force F as the cutting speed increases (Fig. 3). An increase in total cutting force *F* with an increase in feed rate *f* is associated with an increase in the volume of material removed per unit of time. This requires more energy and, at a given tool rotational speed, results in a higher demand for torque and, consequently, for the cutting forces generated at the cutting edges located on the side surface of the applied monolithic ceramic end mill.

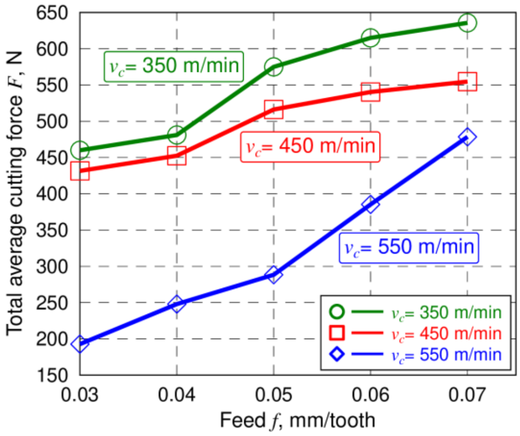

Figure 3. Total cutting force values in the milling process of a gamma aluminide titanium alloy γ-TiAl with a monolithic ceramic milling cutter at various feed rates per tooth *f* and cutting speeds v_c

When machining titanium alloy components with a γ-TiAl intermetallic phase matrix, there is significant wear on the cutting tool edge. This contributes to increasing difficulties in maintaining consistent cutting conditions when machining subsequent surfaces of the workpieces. Furthermore, it becomes more difficult to maintain dimensional tolerances and the surface quality required by the designer. An increase in the components of the cutting force caused by wear of the cutting tool edge during the machining of thin-walled components can lead to significant deformation of the workpiece during machining and the occurrence of large geometric and dimensional errors in the workpiece [15]. During machining with ceramic tools, spalling of the machined surface was observed to a depth of approx. 10 µm (Fig. 4).

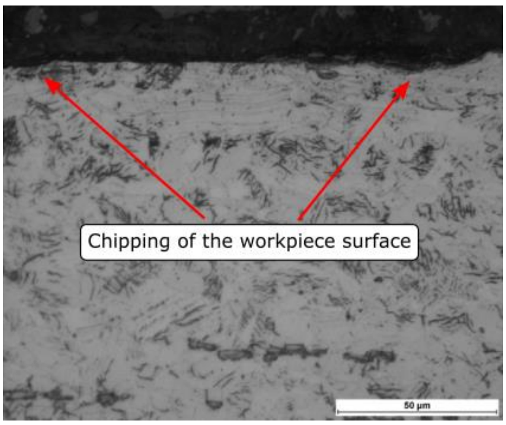

Figure 4. Microstructure of the of gamma aluminide titanium alloy's surface layer with noticeable chipping of the workpiece surface after milling that surface with a monolithic ceramic cutter and cutting speed v_c = 350 m/min, axial depth of cut a_p = 7 mm, radial depth of cut a_e = 0.2 mm and feed rate *f* = 0.05 mm/rev

For the assumed values of cutting parameters, the surface roughness parameter Ra of the machined surface ranges from 0.28 to 1.35 µm, while Rz ranges from 2 to 8 µm.

3.2. Variations of the resistive component of the total cutting force

The exemplary graphs with FFT amplitude spectrum and dominating frequencies of the resistive component of the total cutting force *Fx* variations are shown in Figs. 5 and 6. The values calculated using PSD algorithm were, in most cases, less than 0.5% of the dominant frequency, compared to the values calculated using FFT algorithm. In the worst-case scenario, they were less than 8% different.

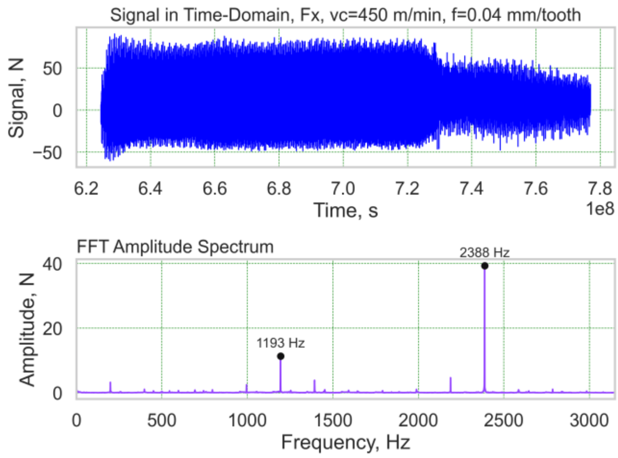

Figure 5. A plot in the time domain of a signal representing the resistive component of the total cutting force *Fx* during a milling process of a gamma aluminide titanium alloy γ-TiAl with a monolithic ceramic milling cutter with a feed rate per tooth of *f* = 0.04 mm/tooth and a cutting speed of v_c = 450 m/min, as well as a plot of the amplitude spectrum of this signal in the frequency domain after applying the Fast Fourier Transform to the signal measured with a force gauge

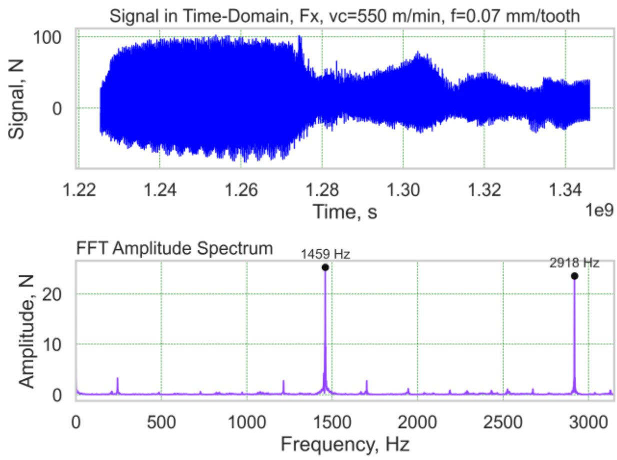

Figure 6. A plot in the time domain of a signal representing the resistive component of the total cutting force *Fx* during a milling process of a gamma aluminide titanium alloy γ-TiAl with a monolithic ceramic milling cutter with a feed rate per tooth of *f* = 0.07 mm/tooth and a cutting speed of v_c = 550 m/min, as well as a plot of the amplitude spectrum of this signal in the frequency domain after applying the Fast Fourier Transform to the signal measured with a force gauge

Knowledge of the dominant frequencies is essential for avoiding resonance frequencies, since operating the machine tool and the rotating tool at a resonance frequency, or even near a resonance frequency, will lead to excessive vibrations of the tool and the workpiece. Consequently, this leads to very large geometric and dimensional errors and even significant damage to the tool and the workpiece.

The dominating frequencies, i.e., 1875 Hz, 2383 Hz and 2930 Hz of the resistive component of the total cutting force *Fx* variations computed with PSD algorithm are shown in Fig. 7.

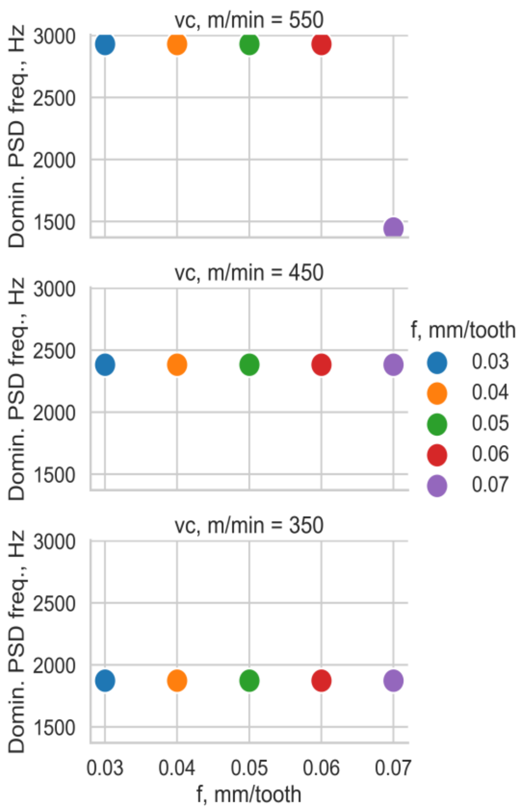

Figure 7. The dominant frequencies determined by computing Power Spectral Density of signals representing the resistive component *Fx* of the total cutting force during a milling process of a gamma aluminide titanium alloy γ-TiAl with a monolithic ceramic milling cutter at various feed rates per tooth *f* and cutting speeds v_c

From the analysis of the results (Fig. 7) it follows that increasing the cutting speed from v_c = 350 m/min to v_c = 550 m/min leads, regardless of the feed rate per tooth *f*, to an increase in the frequency of the *Fx* variations. This effect is largely due to a corresponding increase in the rotational speed of the cutter during the machining process.

The dominant frequency 1445 Hz of *Fx* component of total cutting force variation for the case v_c = 550 m/min and feed rate per tooth *f* = 0.07 mm/tooth is clearly smaller than the other value determined for cutting speed v_c = 550 m/min and feed rate per tooth $f \in \{0.03, 0.04, 0.05, 0.06\}$ mm/tooth which is 2930 Hz. However, the FFT amplitude spectrum graph given in Fig. 6 clearly shows that the difference in amplitudes associated to those frequencies is small.

4. Conclusions

The titanium alloy with an intermetallic matrix γ-TiAl used in performed investigations finds increasingly widespread use in industry due to its excellent strength properties. However, these properties are a source of difficulties in the manufacture of components from these alloys. These difficulties are related, among other things, to a significant tool wear. To counteract this, machining process' parameters are reduced, which, however, results in lower machining productivity.

Therefore, the authors' research interests have focused on monolithic ceramic end mills, which may exhibit lower wear than, for example, solid carbide end mills while maintaining acceptable volumetric machining productivity. However, the material of these monolithic ceramic end mills is characterized by significant brittleness. For this reason, these cutters are sensitive to vibrations, especially variation of forces generated during the machining process. Therefore, the authors focused in their studies on methods for determining the dominant frequencies of the resistive component of the total cutting force *Fx* variations as well as the total cutting force which take place with changes in cutting speed v_c and feed rate per tooth *f*. Thus, section 2 presents the research methodology, describes the experimental setup, and outlines the conditions under which the experiments were conducted. In section 3 total cutting force values in the milling process of a gamma aluminide titanium alloy γ-TiAl with a monolithic ceramic milling cutter at various feed rates per tooth *f* and cutting speeds v_c are shown. Moreover, exemplary FFT amplitude spectrum graphs with dominating frequencies are given. The dominating frequencies computed with PSD algorithm for the cutting speed $v_c \in \{350, 450, 550\}$ m/min are 1875 Hz, 2383 Hz and 2930 Hz, respectively.

The research conducted leads to the following conclusions:

1. Increasing the cutting speed v_c leads to an increase in the dominant frequency of the resistive component of the total cutting force *Fx* variations and to decreasing the total cutting force.
2. Increasing the feed rate per tooth at constant cutting speed v_c increases the total cutting force. However, it has little impact on the dominant frequency of the resistive component of the total cutting force *Fx* variations.

Further research should examine a wider range of variations in process parameters and temperature measurements in the cutting zone, as the heat generated during this process, given the low thermal conductivity of titanium alloy with γ-TiAl matrix used, can significantly affect the rate of tool wear and may affect the accuracy of the shape and dimensions of the machined workpieces, as well as the texture of their surfaces.

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