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Model-based Productivity Analysis of Wire EDM for the Manufacturing of Titanium

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Abstract

For the manufacturing of cost intensive high precision titanium parts for space applications, Wire EDM is without any appreciable alternative when it comes to filigree structures with high aspect ratio, as it allows machining independently of mechanical material properties like hardness or high temperature strength. Nevertheless, cost effectiveness is one of the key factors for guaranteeing a competitive position in high-wage markets like Western Europe. Therefore, an increase of productivity is crucial to maintain reasonable production costs whilst ensuring a consistent or even increasing quality of the part's surface. For that reason, this paper aims to present an analysis of cutting rate related process signal characteristics for Ti-6Al-4V in order to systematically increase productivity including the influence of different wire electrodes.

Keywords: Productivity; Wire EDM; Ti-6Al-4V; Process control; Cutting rate

1. Introduction

With more than 50 % of all titanium tonnage Ti-6Al-4V presently is the most widely used titanium alloy in the world. As a material with a very high mechanical strength to density ratio and an excellent corrosion resistance, titanium is increasingly demanded for aerospace applications, which account for more than 80 % of Ti-6Al-4V usage worldwide. However, titanium alloys are very difficult to machine using conventional machining methods. Due to high chemical reactivity and low heat conductivity, cutting speed must be reduced to less than 1/20 compared to the milling of unalloyed carbon steels in order to prevent work hardening, smearing, galling, and seizing [1, 2].

Wire electrical discharge machining (WEDM) is an energy-based machining process allowing machining independently of mechanical material properties with high competency in machining workpieces with complex shapes [3]. Hence the aerospace industry has recognized WEDM as a valuable and viable process and it is now commonly used to manufacture aerospace and aeronautical components. Especially for applications that require high aspect ratio and precision, state-of-the-art WEDM machines are highly suitable. Nevertheless, machining Ti-6Al-4V WEDM only reaches half the material removal rate compared to milling [4].

The non-existence of particular WEDM cutting technologies for titanium is one reason for suboptimal process productivity for the manufacture of Ti-6Al-4V. Although EDM strategies for materials like steel are well-known, they can't directly be applied on titanium alloys due to their substantially different material properties [5].

In order to enhance cutting productivity, this paper aims to help understand the underlying phenomena when ED-machining Ti-6Al-4V. Therefore, the process signals current and voltage are analyzed varying several machining parameters. Subsequently, the correlation between resulting productivity and specific material properties is examined for Ti-6Al-4V and the powder metallurgic tool steel Vanadis© 23.

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2. State of the Art and Experimental Setup

The compositions of the titanium alloy Ti-6Al-4V (3.7164) and the powder metallurgical tool steel Vanadis23 (1.3395) are shown in Table 1.

Table 1: Chemical composition by wt.%

Titanium alloy Ti-6Al-4V

Fe	O	N	C	H	Al	V	Ti
0-0.40	0-0.20	0-0.05	0-0.08	0-0.015	5.50-6.75	3.50-4.50	B

Tool steel Vanadis23

C	Cr	Mo	W	V	Fe
1.28	4.1	5.0	6.4	3.1	B

Different material properties result in different cutting behaviors. For EDM, electrical and thermal properties play a crucial role in a material's machinability [6]. Therefore, an understanding of the relationship between material characteristics and cutting behavior is necessary. The thermo-physical properties of Ti-6Al-4V and Vanadis23 are shown in Table 2.

Table 2: Physical properties of Ti-6Al-4V and Vanadis23 at 20 °C

	ρ (kg/m³)	ρ_s (Ωmm²/m)	T_m (K)	λ (W/mK)	c (J/kgK)
Ti-6Al-4V	4430	1.71	1905	6.6	580
Vanadis23	7980	0.54	1673	24	420

In the literature several concepts exist to describe the ease of ED-machining different materials based on their thermo-physical properties. These are the Erosion Resistance Index (C_m), first introduced by Reynaerts [7] and later expanded by Meeusen [8] as well as the λ-θ-theory by Mohri [9] and the λ-θ-ρ_s-theory by Mahardika [10]. All four concepts predict a superior ease of ED-machining for Ti-6Al-4V compared to the tool steel Vanadis23 although none of the concepts can make a quantitative prediction. The underlying equations as well as the resulting coefficients can be found in Table 3.

Table 3: Concepts to describe the material specific ease of ED-machining

	C_m Reynaerts [7]	C_m (Meeusen)	λ-θ-theory (Mohri)	λ-θ-ρ_s-theory (Mahardika)
Formula	$\lambda \cdot c \cdot T_m^2$ $(10^{12} \cdot \frac{J^2}{m \cdot K \cdot s})$	$\lambda \cdot \rho \cdot c \cdot T_m^2$ $(10^{13} \cdot \frac{J^2}{m^4 \cdot s})$	$\lambda \cdot T_m$ $(10^3 \cdot \frac{W}{m})$	$\lambda \cdot T_m \cdot \rho_s$ $(10^{-2} \cdot W \cdot \Omega)$
Ti-6Al-4V*	0.014	6.15	12.6	2.15
Vanadis23*	0.028	22.51	40.2	2.17

*Lower values indicate better ED-machining; different coefficients are not intercomparable.

A lower thermal conductivity λ and melting point T_m have a positive effect on the machinability [10, 11]. A lower thermal conductivity prevents heat from dissipating quickly into the workpiece. With a lower melting point, less energy is required to melt workpiece material. A low specific electrical resistance enables a better transfer of electric current [5]. This positively affects the formation of the discharge channel and usually results in a shorter discharge delay time t_d as well as an increasing discharge energy W_e [12].

3. Experimental Setup and Signal Analysis

The experiments were conducted on a GFMS Cut P550 Wire EDM machine. During wire machining the electrical conductivity of the dielectric water was maintained at ~10 µS/cm. Two types of wires were used for the tests: an uncoated brass wire (bercocut© pro, material: CuZn36) and a zinc-coated gamma-phase wire (topas© plus H, core material: CuZn36) both with a diameter of d = 250 µm. The flushing nozzels were set in a distance of h_F = 0.05 mm above and below the workpiece (height h = 30 mm) to guarantee best flushing conditions. A cut with a length of l_c = 10 mm was performed to determine cutting speed (CS) and thus cutting rate (CR). Prior to this measuring section a triangular shape was machined to inhibit the dielectric fluid from flowing out of the arising side gap, as described by Welling [13].

In Table 4, all machine parameters are shown. CS and thus CR are mainly influenced by discharge current i_e, discharge duration t_e and pause duration t_0. The machine parameter I determines the directly dependent physical parameters discharge current i_e and discharge duration t_e, while the machine parameter P sets the discharge frequency f_e by determining the pause duration t_0. All other machine parameters were set to values that guaranteed stable machining conditions throughout the range of variation of I and P as well as a maximum of comparability.

Table 4: Machine Parameters (several: non physical meaning)

Varied Machine Parameters	Ti-6-Al-4-V	Vanadis23
I (det.* i_e and t_e)	15, 17, 19	15, 17, 19
P (det. t_0)	41, 46, 51	41, 46, 51
Fixed Machine Parameters		
Ssoll	45	45
ISH (det.* $i_{e,short}$)	-3	-3
TON (det. t_{on})	32 (no limit)	32 (no limit)
SPL (short pulse limit)	7	7
Flushing pressure (bar)	10	10
Wire speed (m/min)	10.8	10.8
Wire tension	17	17

*det.: determining

Setting the machine-integrated control of the short pulse current $i_{e,short}$ to a level of ISH = -3 resulted in a nearly constant ratio of i_e and $i_{e,short}$ of R_i = 0.75. All other machine controls have been switched off, so that the settings of I and P could not be compromised by the machine itself.

The machine also tracks the number of consecutively occurring abnormal discharges pulses. This prevents unstable machining conditions and gap conditions that could lead to wire breakage. SPL (short pulse limit) defines a limit of permitted consecutive short pulses that are followed by a macroscopic pause of $t_{0,m} \approx 650$ µs to restore stable gap conditions. A value of SPL = 7 was set which equals 15 consecutive short pulses before a macroscopic pause $t_{0,m}$ is performed.

An oscilloscope was used to record current i and voltage u for three periods of $t_r = 200$ ms distributed over the cutting length as soon as the cutting process had reached a stable state and steady flushing conditions. In order to process and evaluate the oscilloscope's raw data a Matlab© script was developed that allows to distinguish all different phases of each single discharge. It qualifies the discharges as main or short pulse and quantifies single pulse energy E_e, duty factor τ, ignition delay time t_d, discharge frequency f_e as well as the percentage of short pulses R_s.

4. Results and Discussion

For the analysis of the material specific machining phenomena of Ti-6-Al-4-V main cuts with two wire types have been conducted and compared to the performance of Vanadis23 regarding cutting rate. As predicted by the coefficients, cutting rates in titanium were much higher in titanium than in steel. Averaged over all parameter settings (I, P) CR is around 25 % higher than in Vanadis23 using the standard brass wire. The increase in CR strongly depends on the setting of machine parameters I and P, showing two main trends. The gain in CR for titanium increases proportionally to I and inversely proportional to P. While cutting rates differ by around 50 % for the lowest setting of P, the highest setting of P only shows gains of around 20 %. The same applies for I the other way round. It has to be noted that the lowest setting of I = 15 does not match the above description but shows a constant relative gain of 10 % of titanium over steel.

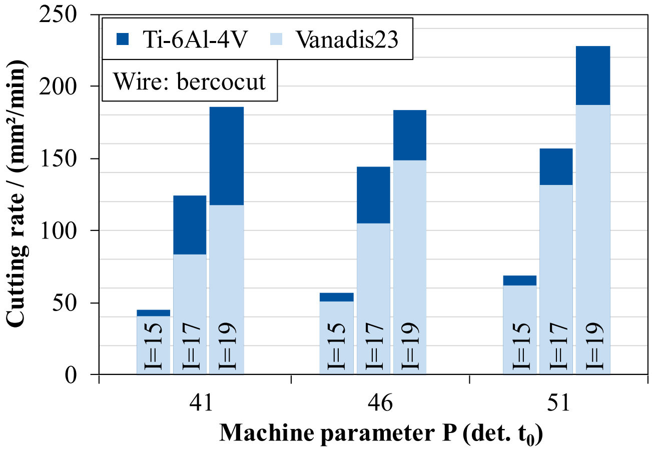

Fig. 1: Cutting rate Ti-6Al-4V vs. Vanadis23

The hypothesis is that the two described trends of above-average growth of CR are attributable with the differences in thermo-physical properties of Ti-6Al-4V and Vanadis23. Namely the lower thermal conductivity λ_{Ti} (factor 3.5) seems to be a main factor at least for the relation of gain of CR and setting of I.

Using the zinc coated gamma phase wire (topas plus H) once more an over-proportional increase in CR for titanium can be found, see Fig. 2. Regarding machine parameter I, both materials show a nearly constant increase of CR according to amount. The CR in Ti-6Al-4V on average increases by 35 mm²/min or 28%, while CR in Vanadis23 medially increases by 11.5 mm²/min or 12 %.

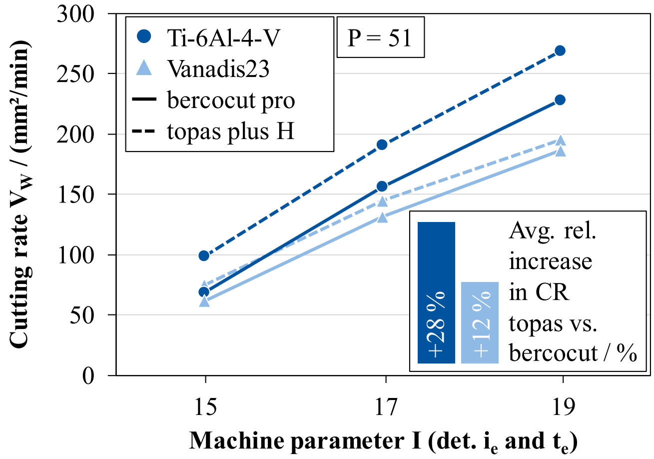

Fig. 2: Cutting rate increase using gamma-phase wire

During signal analysis with the Matlab script more than 30 factors were distinguished after extraction from the process signals current i and voltage u. With the means of analysis of variance (ANOVA), the main three factors were determined that, dependently on the material, show the strongest correlation to the cutting rate. These are

- maximum discharge current i_{max},
- average discharge energy of a single pulse W_e and
- average discharge power P_e.

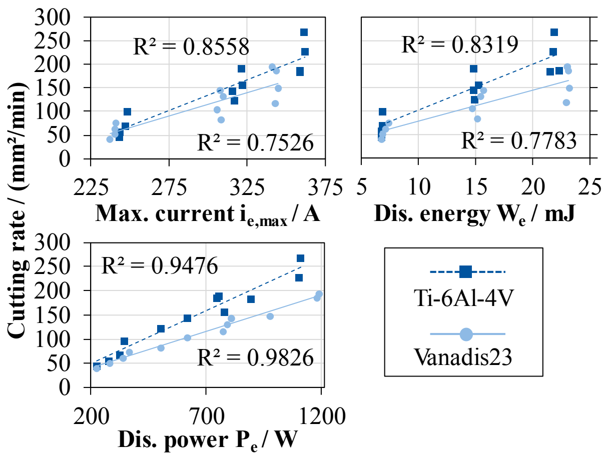

Fig. 3: Main signal factors determining the cutting rate

Unlike the average and maximum discharge current $i_{e,av}$ and $i_{e,max}$ the discharge voltage u_e does not show a good correlation to the reached CR. Mainly the discharge energy of a single pulse W_e and the mean discharge power P_e that includes also the discharge frequency f_e, determine the resulting cutting rate. Although the mean discharge energy and power W_e and P_e machining steel are about 4 % higher the resulting cutting rates are lower than in titanium because of the substantially different material properties. To understand the specifics of the machining of Ti-6Al-4V, Fig. 4 shows the differences in signal response between the two materials when machined by the same process parameters. It can be seen that the maximum and average voltage $u_{e,av}$ and $u_{e,max}$ are reduced by 10 % respectively 3 % while the average discharge current is only increased by 2 %. This causes the discharge energy W_e to decrease by 4 %. Due to the reduced discharge frequency f_e of

-0.6 % the discharge power P_e decreases even more with about 5 %.

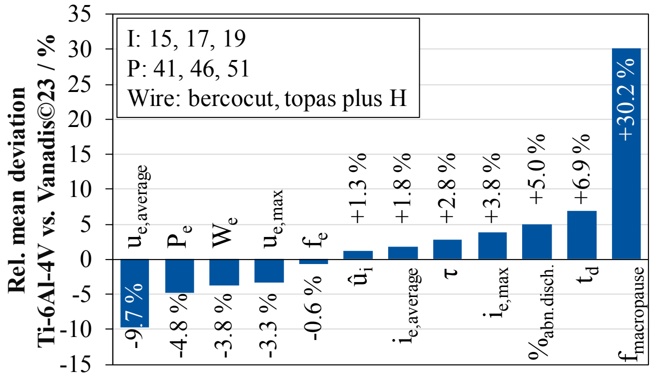

Fig. 4: Relative mean deviation of several signal factors

Further the process signal of the titanium machining shows a 5 % increase in abnormal discharges compared to steel. This seems to be closely linked to the probability of process instability occurrence. Latter are indicated by the highly increased frequency of macroscopic pauses f_{macro} (+30 %) that are applied by the machine in case a critical number of abnormal discharges is detected. The higher number of macroscopic pauses accounts for 0.6 % of the total machining time which is exactly the amount by which the discharge frequency is decreased.

The discharge delay time t_d is increased by 7 % when machining Ti-6Al-4V. This also affects the duty factor τ, increasing by approximate 3 %. This is in accordance with [12], stating that a higher electrical resistance (three times higher for Ti-6Al-4V) results in extended discharge delay times. The same applies to the drop in discharge voltage and thus discharge energy.

Irrespective of the diminished energy and power, cutting rates in titanium are much higher than in steel. This is consistent to the predictions made by all four of the concepts for the ease of ED-machining.The coefficients' ratio (titanium : steel) varies between 1 : 3.6 (Meeusen) and 1 : 1.01 (Mahardika). It should be noted that according to the Wiedemann-Franz law the approximately constant Lorenz-Number L proportionally connects electrical and thermal conductivity. This means thermal conductivity λ and specific electrical resistance ρ_s are linked inversely proportional. The inclusion of both λ and ρ_s into the equation of Mahardika therefore signifies a stronger representation of the melting temperature $T_{m'}$ and is therefore of less informative value.

The favored explanation for the high cutting rates in Ti-6Al-4V is that the much lower (factor 3.5) thermal conductivity λ accounts for the majority of the productivity increase, compensating for the higher melting temperature T_m (factor 1.14) and the worse electrical resistivity (factor 3.2). The λ-θ-theory and the ERI by Meeusen so far seem to fit the experimental results fairly good. They have to be proven by expanded test with other materials.

5. Summary and Outlook

Main cuts in Ti-6Al-4V and Vanadis23 have been conducted using two different types of wires and varying the machine parameters I and P. The recorded process signals have been evaluated highlighting material specific differences. A further investigation of the logical combination and quantification of material properties and their characteristic representation in process signals should follow. Together with an advanced and more sophisticated approach to predict the ease of ED-machining these will enable a better understanding of the possibilities to systematically improve a materials' machining.

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