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Experimental research on electrodischarge drilling of high aspect ratio holes in Ti-6Al-4V alloy

Badania elektroerozyjnego drążenia głębokich otworów w stopie tytanu Ti-6Al-4V

Abstract

The drilling of small cylindrical (D < 1 mm) holes with a high ratio of length to diameter (L/D > 10) in difficult-to-cut materials is significantly beyond mechanical drilling capabilities. Electrodischarge machining (EDM) is a good and cost effective alternative in such situations. The machinability of electrodischarge machined material is determined by its thermal and electrical properties; therefore, the high electrical resistivity, the relatively high melting point and low thermal conductivity of Ti-6Al-4V alloy cause problems during the machining of parts made of this material. In this article, the results of experimental research on electrodischarge microdrilling in Grade 5 Ti-6Al-4V alloy are presented. The influence of various machining parameters (pulse time, discharge voltage, current amplitude, dielectric pressure, electrode-tool rotation speed) on key technological factors such as hole depth, side gap, linear tool wear, mean drilling speed and hole taper angle was analysed.

Keywords: EDM, holes with a high ratio of length to diameter, drilling, titanium

Streszczenie

Drążenie cylindrycznych otworów o małych średnicach (D < 1 mm) charakteryzujących się dużą smukłością (L/D > 10) w trudnoskrawalnych materiałach wykracza poza możliwości konwencjonalnych metod wiercenia. Obróbka elektroerozyjna jest dobrą i efektywną alternatywą dla tego typu zastosowań. Obrabialność w EDM jest zdeterminowana przez właściwości związane z przewodnością cieplną i elektryczną obrabianego materiału oraz dielektryka. Wysoki opór elektryczny i relatywnie wysoka temperatura topnienia, przy niskiej przewodności cieplnej stopu tytanu Ti-6Al-4V, powodują pewne problemy podczas jego obróbki, co stwarza konieczność poszukiwania jej optymalnych parametrów. W artykule przedstawiono wyniki badań doświadczalnych procesu mikrodrążenia elektroerozyjnego stopu tytanu Ti-6Al-4V. Badano wpływ parametrów obróbki takich jak: czas impulsu, wartość napięcia pracy i amplitudy prądu, ciśnienia dielektryka, prędkości obrotowej elektrody roboczej na podstawowe wskaźniki technologiczne oraz dokładności wymiarowe i kształtowe.

Słowa kluczowe: EDM, drążenie, tytan, głębokie otwory

1. Introduction

Over recent years, a progressive tendency for the production of miniaturised parts can be observed – this is compliant with the principle: smaller, faster, cheaper. This trend has now become a primary object of interest in many industries, such as aviation, automotive, and electronics (area of the MEMS (microelectromechanical system) production). In the abovementioned branches of industry, along with progressing miniaturisation, one can notice an increasing demand for effective techniques of micro-hole production with diameters from 8 to 500 μm and aspect ratios above 20: 1. For example, during the production of jet engines, a lot of holes are made (20,000–40,000) in the turbine, combustion chamber and stator units. Often, as in the case of turbine blades that are cast, internal cooling channels are created by placing special ceramic cores in the moulds. However, improving the quality of the surface obtained in such a manner requires the use of special abrasive pastes, which results in a longer production cycle. Unconventional methods (e.g. electrodischarge machining, laser beam machining, electrochemical machining) are used for the production of holes.

In addition to the growing demand for effective and efficient micro-production techniques, there are increasing requirements for the quality of the internal surface of drilled micro-holes and their dimensional and shape accuracy. Very often items that require drilling are made of difficult-to-cut materials.

For the construction of aircraft components, turbine engines mainly use materials such as titanium alloys, nickel alloys, steels, nickel-based superalloys. Physical and strength properties of these materials (high ductility, high specific strength, tendency to strengthen during machining, higher hardness) make it impossible to effectively drill micro-holes in them using conventional machining [1].

During electrodischarge machining (EDM), material is removed from the workpiece as a result of the energy of pulsed electrical discharge between two electrodes immersed in a liquid dielectric medium. During this process, the material melts and evaporates in the discharge. Machinability in the EDM process does not depend on the mechanical properties of the workpiece, but only on its electrical and thermal conductivity; this causes this type of machining to be often used for hard-to-cut materials [2–5].

Disadvantages of spark erosion machining include electrode wear, deformed shape of the obtained hole (conical shape), and heat-affected top layer of the workpiece surface [6–9]. In some cases, additional finishing operations are also required [10]. High temperature in the discharge zone causes a heat-affected zone, which can lead to a change in the mechanical properties of the surface layer (formation of microcracks, additional stresses or porosities) [11].

During the drilling of holes using EDM, the working electrode moves towards the material and also rotates (Fig. 1). The dielectric is supplied into the machining area through a channel in the electrode which enables better removal of the products of erosion. Various types of oil-based liquids or deionized water are used as a dielectric; however, in the case of deep hole drilling, deionised water is preferred.

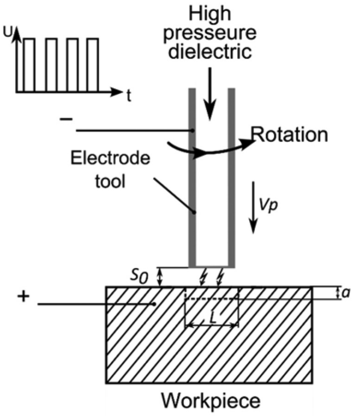

Fig. 1. Scheme of the EDM drilling process

EDM is a technology used in the machining of titanium and its alloys, especially in the case of microdrilling. Due to the mechanical, thermal and chemical properties of these materials, conventional machining is difficult; therefore, EDM is good alternative to other machining methods, especially when complicated or when a shape with a high ratio of length to diameter has to be machined [12–15].

This paper concerns electrodischarge drilling of Grade 5 Ti-6Al-4V alloy. This material is characterised by its high temperature and corrosion resistance, high strength factor and excellent mechanical properties and is commonly applied in the aircraft and space industry. However, due to its high level of chemical reactivity low thermal conductivity, conventional machining of Grade 5 alloy is difficult; EDM is therefore a good machining alternative [1, 16, 17]. It is worth stressing that in comparison to the materials most commonly machined using EDM, Ti-6Al-4V alloy has high electrical resistivity (five times larger than common steel), a relatively high melting point and low thermal conductivity [17, 18, 19]. It is also important that the electrical resistivity of Ti-6Al-4V alloy be highly dependent on the temperature. On the basis of the abovementioned features, one can state that machining of this material is characterised by rapid heat generation (because of low electrical conductivity) and problems with heat dissipation. This results in low productivity and poor surface integrity.

The results of previous research concerning EDM drilling in Grade 5 highlight the following problems: obtaining of high aspect ratio *see above note* hole for diameters less than 1 mm, hole taper, white layer formation and microcracks [18].

In this article, the results of experimental research on electrodischarge microdrilling in Grade 5 Ti-6Al-4V alloy are presented. During the experiment, the influence of following machining parameters were applied: voltage pulse time, discharge voltage, current amplitude, dielectric pressure and electrode-tool rotation speed. The impact of these parameters on hole depth, side gap, linear tool wear, mean drilling speed and hole taper angle was analysed.

2. Research methodology

The research was carried out on a machine tool designed and built at the Institute of Production Engineering of Cracow University of Technology (Fig. 2). Titanium alloy Ti-6Al-4V was used as the machined material. This is an alloy often used in the aerospace and biomedical industries, characterised by very good mechanical properties, relatively low density, high corrosion resistance and high strength at high temperature. The test stand consists of several components of which the most important are:

- mechanical part of the machine with servo drives, electrode, sample grip and electrode guide,
- pulse generator with power supply,
- high pressure system for dielectric circulation,
- drive control system.

An important element was the electrode guide (Fig. 3), which allowed minimising the impact of electrode vibrations and clamping eccentricity on the drilling process.

The main goal of the research was to examine the impact of process parameters on efficiency, accuracy, electrode wear and drilling speed. The research was performed according to the design of the experiment. Table 1 shows the input and output parameters used during the tests.

Table 1. Research input and output parameters

Input parameters	**min**	**max**
Time of the pulse t_i [μs]	100	999
Current amplitude I [A]	2.00	4.65
Discharge voltage U [V]	60	120
Dielectric inlet pressure p_{in} [bar]	50	90
Electrode rotation speed ω [1/min]	100	500
Output parameters		
Linear tool wear (TW) [%]		
Side gap(S) [μm]		
Taper angle(α) [deg]		
Drilling speed (v) [μm/s]		
L/D ratio		

The shape, dimensions and material of the tool electrode were kept constant throughout the testing (single channel, 0.4 mm diameter, made of copper); similarly, the dielectric fluid was deionised water for the duration of the experiment. Each sample had a thickness of 10 mm and the holes were drilled through the entire depth of the samples. To avoid problems with through drilling, an additional technological pad was applied on the underside of sample

(Fig. 2). Full quadratic (constant, linear, interaction, and squared terms) polynomial was selected in order to statistically fit experimental data. Matlab software was used to calculate the polynomial coefficients and perform a regression analysis.

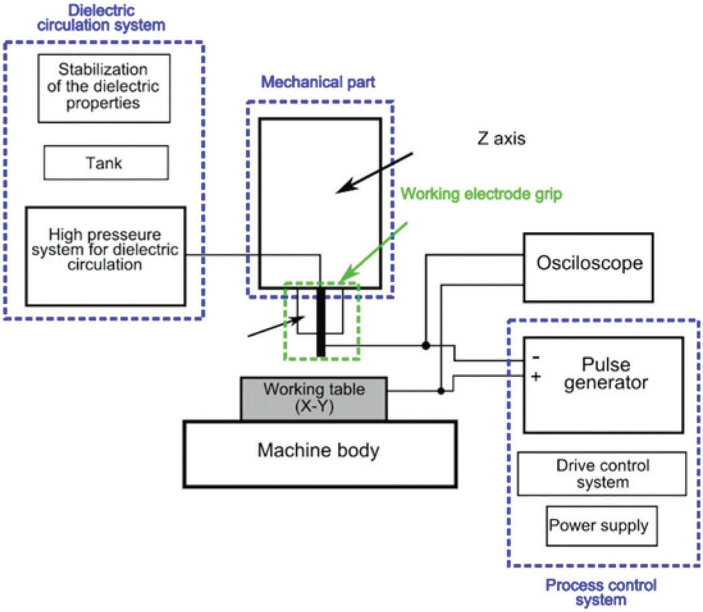

Fig. 2. Scheme of the test stand and its main functional units

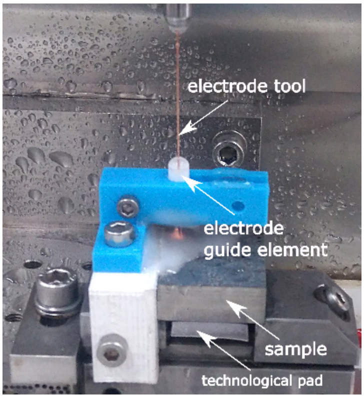

Fig. 3. Photography of the electrode guide system

3. Results analysis

During the research, the influence of five input parameters on technological factors was investigated. This allowed testing which factors – apart from the most important parameters such as current amplitude and pulse time (Fig. 4) – affect the efficiency of the electrodischarge drilling process.

The electrical parameters have the largest impact on drilling speed and side gap thickness (Figs. 4, 5 and 6); however, optimal selection of rotation speed and dielectric inlet pressure gives the possibility to obtain much better results of selected technological factors.

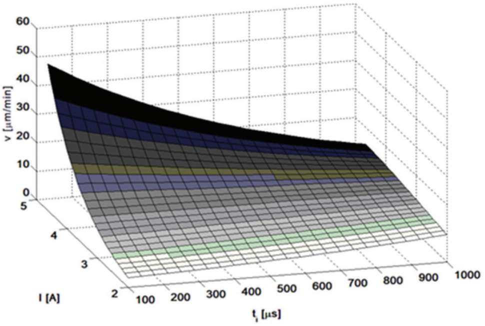

Fig. 4. Relationship of drilling speed v, current amplitude I and pulse time t_i, discharge voltage U = 100 V, dielectric inlet pressure p_{in} = 70 bar, electrode rotation speed ω = 300 rpm

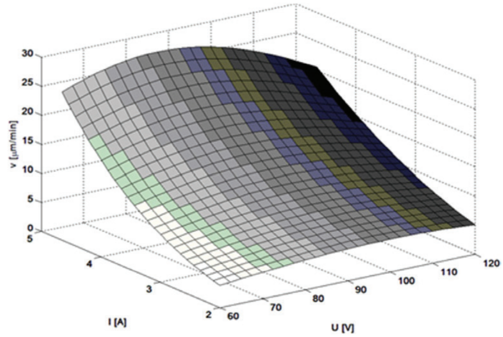

Fig. 5. Relationship of drilling speed v, current amplitude I and discharge voltage, pulse time t_i = 550 μs, dielectric inlet pressure p_{in} = 70 bar, electrode rotation speed ω = 300 rpm

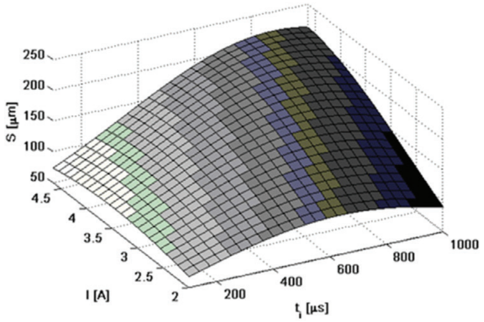

Fig. 6. Relationship of side gap S, current amplitude I and pulse time t_i, discharge voltage U = 100 V, dielectric inlet pressure p_{in} = 70 bar, electrode rotation speed ω = 300 rpm

Results relating to the relationship between L/D ratio and dielectric inlet pressure (Fig. 7) indicate that, when other machining parameters are kept constant, increase of dielectric pressure improves the L/D ratio. Taking into account that each hole depth was 10 mm, this means that hole diameter decreases. Better frontal and side gap flushing means that erosion products from the discharge area are removed more efficiently (dielectric is 'fresh') and a smaller gap is necessary to initiate the discharge.

In Fig. 8, the relationship between drilling speed v and electrode rotation speed ω is presented. With increase of ω – when other machining parameters are kept constant – drilling speed also increases. Rotation of the electrode tool improves the evacuation of the machining products from the gap and also gives the possibility to obtain a hole with better circularity (see Fig. 11d); however, this effect is connected with the improvement of electrode stiffness. For an electrode diameter of D = 0.4 mm and a L/D ratio higher than 10, the eccentric effect becomes significant. Increase of electrode tool rotation speed gives the possibility to minimalise the eccentric effect.

It is worth emphasising that drilling speed decreases with increases to dielectric pressure (Fig. 9). This is due to a loss of dielectric continuity and the dielectric-air mixture which occurs and in the gap. This results in a decrease of the frequency of effective discharges and their efficiency; as a result, machining speed decreases. Contrastingly, increase in dielectric inlet pressure and an increase of discharge effectiveness cause a decrease of tool wear.

The amount of removed material depends on single pulse discharge which is related to discharge current amplitude, discharge voltage and pulse time. Results observable in Figs. 11a, 11b and 11c indicate that an increase of these technological factors significantly affect the hole diameter and quality. Change of dielectric pressure and electrode-tool rotation speed influences flushing efficiency.

It is worth mentioning that because the hole depth was 10,000 μm, the mean taper angle calculated for the drilled holes was 0.4 of a degree.

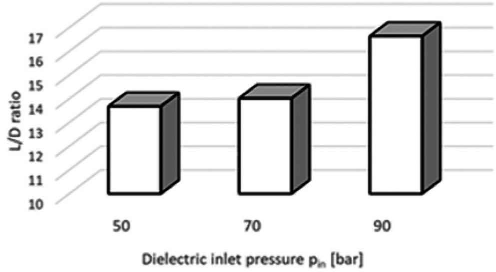

Fig. 7. Relationship of L/D ratio and dielectric inlet pressure; t_i = 550 μs, I = 3,33 A, U = 100 V, ω = 300 rpm

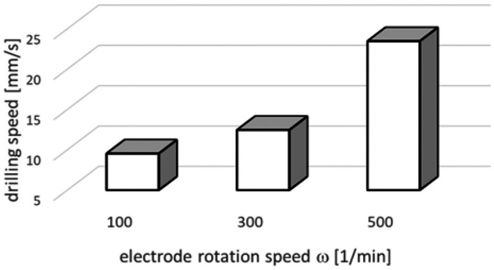

Fig. 8. Relationship of drilling speed and electrode rotation speed ω, t_i = 550 μs, I = 3,33 A, U = 100 V, p_{in} = 70 bar

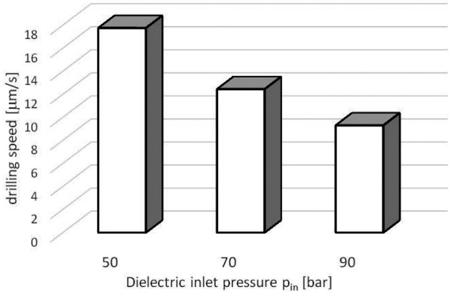

Fig. 9. Relationship of drilling speed and dielectric inlet pressure; t_i = 550 μs, I = 3,33 A, U = 100 V, p_{in} = 70 bar

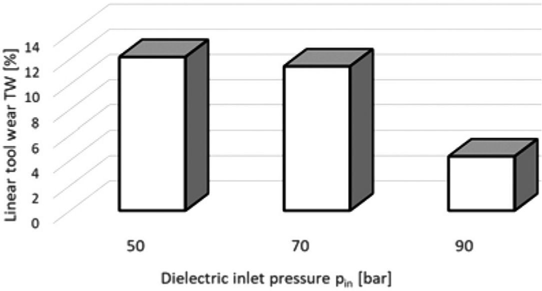

Fig. 10. Relationship of linear tool wear and dielectric inlet pressure; t_i = 550 μs, I = 3,33 A, U = 100 V, ω = 300 1/min

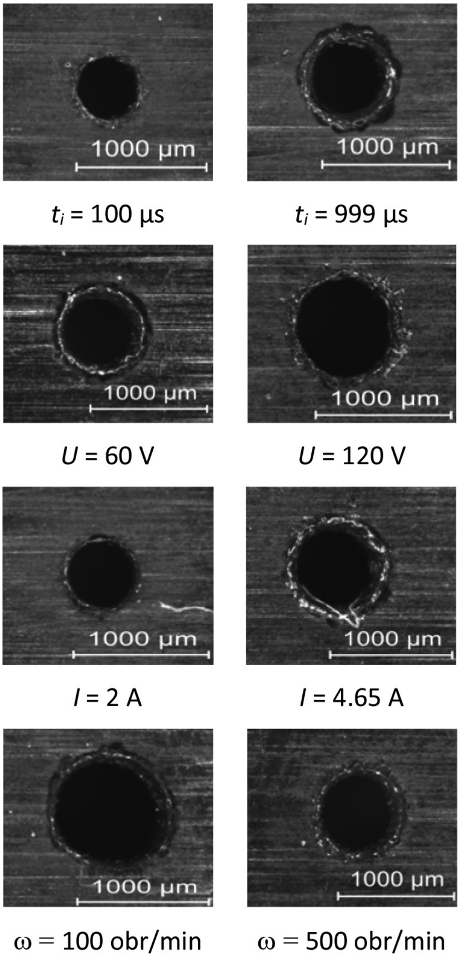

Fig. 11. Photographs of entrance hole for extreme values of pulse time t_i (a), discharge voltage U (b), current amplitude I (c) and electrode-tool rotation speed (d); other input parameters are from the centre of the research plan (t_i = 550 µs, I = 3,33 A, U = 100 V, p_{in} = 70 bar, ω = 300 rpm)

4. Summary

The conducted research proved that electrodischarge machining is a good alternative for conventional methods when drilling high aspect holes in Grade 5 Ti-6Al-4V alloy. It gives the possibility to drill through holes (L/D ratio above 15) with relatively high efficiency (the drilling speed reaches 3 mm/min). The analysis of the results allows formulation of the following conclusions:

- Dielectric inlet pressure and electrode rotation speed have significant influence on hole depth. Increase of dielectric inlet pressure leads to better gap cleaning, which results in a decrease of tool electrode wear and in a decrease of drilling speed. This can be explained by a decrease of discharge energy, despite of increase of the process effectiveness. Therefore, one can state that the selection of optimal dielectric pressure is a compromise between machining speed and tool wear.

- Increase of electrode tool rotation speed leads to an increase of drilling speed. Electrode rotation with a relative high speed (ω = 500 1/min) results in the efficient cleaning of the machining area, which directly contributes to an increase in process efficiency. Tool rotation also improves axial symmetry, but in the case of eccentricity, it can increase hole diameter.
- Due to the thermal and electrical properties of the machined material, the quality of the inlet and outlet holes is not perfect; thus, further research focused on surface integrity is needed.

References

[1] Percina M., Aslantas K., Ucuna I., Kaynakb Y., Cicekc A., *Micro-drilling of Ti–6Al–4V alloy: The effects of cooling/lubricating,* Precision Engineering, Vol. 45/2016, 450–462.

[2] Rajurkar K.P, Sundaram M.M., Malshe A.P., *Review of Electrochemical and Electrodischarge Machining,* Procedia CIRP, Vol. 6/2013, 13–26.

[3] Skoczypiec S., Machno M., Bizoń W., *The capabilities of electrodischarge microdrilling of high aspect ratio holes in ceramic materials,* Management and Production Engineering Review Vol. 6-3/2015, 61–69.

[4] Plaza S., Sanchez J.A., at all, *Experimental study on micro EDM-drilling of Ti6Al4V using helical electrode,* Prec. Eng. Vol. 38/2014, 821–827.

[5] Skoczypiec S., Ruszaj A., *A sequential electrochemical-electrodischarge process for micro part manufacturing* Prec. Eng., Vol. 38/2014, 680–690.

[6] Hasan M., Zhao J., Jiang Z., *A review of modern advancements in micro drilling techniques* Journal of Manufacturing Process, Vol. 29/2017, 343–375.

[7] Kliuev M., Baumgart C., Wegener K., *Fluid dynamics in Electrode Flushing Channel and Electrode-Workpiece Gap During EDM Drilling,* "Procedia CIRP", Vol. 68/2018, 254–259.

[8] Li J., Yin G., Wang C., Guo X., Yu Z., *Prediction of aspect ratio of a micro hole drilled by EDM* "Journal of Mechanical Science and Technology", Vol. 27/2013, 185–190.

[9] Kamal K., Rawalb S.K., Singha V.P., Anu B., *Experimental Study on Diametric Expansion and Taper Rate in EDM Drilling For High Aspect Ratio Micro Holes in High Strength Materials,* "Materials Today: Proceedings", Vol. 5/2018, 7363–7372.

[10] Risto M., Haas R., Munz M., *Optimization of the EDM drilling process to increase the productivity and geometrical accuracy,* "Procedia CIRP" Vol. 42/2016, 537–542.

[11] Mowwer T.D., *Degradation of titanium 6Al–4V fatigue strength due to electrical discharge machining,* "International Journal of Fatigue", Vol. 64/2014, 84–96.

[12] Manjaiah M., Narendranath S., Basavarajappa S., *A review on machining of titanium based alloys using EDM and WEDM,* "Rev. Adv. Mater. Sci." Vol. 36/2014, 89–111.

[13] Antar M., Chantzis D. et al., *High Speed EDM and Laser Drilling of Aerospace Alloys,* "Procedia CIRP", Vol. 42/2016, 526–531.

[14] Hasçalık A., Çaydas U., *Electrical discharge machining of titanium alloy (Ti–6Al–4V)*, "Applied Surface Science", Vol. 253/2007, 9007–9016.
[15] Sanchez J. A., Plaza S., et al., *Electrode set-up for EDM-drilling of large aspect-ratio microholes*, "Procedia CIRP" Vol. 6/2013, 274–279.
[16] Ezugwu E.O., Wang Z.M., *Titanium alloys and their machinability – a review*, "Journal of Materials Processing Technology", Vol. 68/1997, 262–274.
[17] Hascalik A., Caydas U., *Electrical discharge machining of titanium alloy (Ti–6Al–4V)*, "Applied Surface Science", Vol. 253/2007, 9007–9016.
[18] Wansheng Z., Zhenlong W., Schichun D., Guanxin C., Hongyu W., *Ultrasonic and electro discharge machining to deep and small hole on titanium alloy*, "Journal of Materials Processing Technology", Vol. 120/2002, 101–106.
[19] Fonda P., Wang Z., Yamazaki K., Akutsu Y., *A fundamental study on Ti–6Al–4V's thermal and electrical properties and their relation to EDM productivity*, "J. Mater. Process. Technol", Vol. 202/2008, 583–589.

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