euspen's 21st International Conference & Exhibition, Copenhagen, DK, June 2021
www.euspen.eu

Near-dry die-sinking EDM of CrCoMo dental implant structures

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Abstract

Electrical discharge machining (EDM) is used in dental industry for manufacturing of high-precision dentures from hard non-precious alloys (CrCoMo) and titanium alloys. Conventional dental EDM machines have a restricted working space due to the use of a liquid dielectric and the associated machine periphery, in particular, the dielectric basin. Compared to conventional EDM, near-dry EDM uses liquid and gas mixtures as a dielectric, which increases the flexibility of the machining process due to the independence from the liquid dielectric periphery. This leads to miniaturization of the machine components and increased integrability into different hybrid machine concepts.

This paper presents the strategy and technology of near-dry EDM of CrCoMo dental bridges. A water-air mixture, which is injected through the copper tool electrode into the erosion zone by a specially developed flushing system is used as a dielectric. In order to increase the efficiency of the near-dry EDM process, the basic relationships between the energy-influencing process variables and the flushing parameters are investigated experimentally. A reproducible surface structure, atypical for electroerosion machining, could be achieved depending on the flow rate and composition of the spray mist used. Using the design of experiments, the correlation between the achieved surface structure and the electrode wear rate V_E as well as the average surface roughness Ra is investigated.

Keywords: near-dry electrical discharge machining (EDM); electrode rinsing system; CrCoMo

1. Introduction and state of the art

Electrical discharge machining (EDM) enables contactless and almost force-free machining of all electrically conductive materials with an electrical conductivity of at least $\kappa \leq 0{,}01$ S/cm. This means that EDM can be used for machining materials such as high-alloy hardened steels or high-performance ceramics. In dental technology EDM is used, among other things, for the manufacture of high-precision dental prothesis structures made of chromium-cobalt-molybdenum alloys (CrCoMo) or titanium alloys.

To prevent the premature loss of prosthetic implants, the prosthetic structure screwed onto the implant must be positioned tension-free and bacteria-proof [1]. This can be achieved by the manufacturing process consisting of the following three steps [1]. In the first step the prosthetic structure is fabricated by a casting or milling process. This is followed by a roughing operation using die-sinking EDM, which eliminates the inaccuracies caused by milling or casting the workpieces. Finally, the surface roughness of Ra ≤ 2 µm, required to prevent bacterial deposits, is achieved by the finishing process using µ-EDM [2].

Currently, liquid dielectrics on synthetic or mineral oil-based hydrocarbon compounds are used for EDM processes in the dental industry. Among other things, the dielectric is responsible for the removal of ablation particals from the machining zone. The high density of the oil-based liquid dielectric as well as the small working gap s present during the electrical discharge machining of implant structures and the associated unfavorable flushing conditions lead to a strong contamination of the working gap s and consequently to a reduction in the quality of the produced surfaces.

To achieve improved flushing conditions in the working gap s, a low-viscosity liquid-gas mixture can be used. The use of a liquid-gas mixture as a dielectric is called near-dry EDM and was first investigated by Tanimura et al. [3]. In these investigations, a deionized water and a kerosene based spray mist mixed with air, nitrogen or argon was used as a dielectric, thus achieving a stable machining process. Further studies on near-dry EDM conducted by Kao et al. [4,5] showed that a smaller working gap s can be achieved with lower discharge energy W_e and higher material removal rate V_w compared to conventional EDM. In addition, the liquid-gas mixture, which can be controlled according to the requirements of near-dry EDM, enables an improved removal of the removed particles compared to dry machining. This prevents the particles from adhering to the surface and allows good integrity of the machined surface to be achieved [5-7].

Other work dealt with the investigation of different dielectrics, such as water-oxygen, water-nitrogen and glycerin-air mixture, which can be used in the near-dry EDM drilling and milling process, as well as with the test of different electrode flushing strategies. Tao et al. [7] concluded that nitrogen and helium gases prevent electrolysis and thus achieve a better surface finish in near-dry EDM drilling and milling. Further, the research by Natsu et al. [8] showed that the injection of atomized deionized water into the lateral gap area of the micro hole milling process increases the machining accuracy compared to water jetting due to the reduced electrolysis.

The mist jet leads to an increased removal of particles from the working gap area and simultaneously increases the material removal rate V_w. Dhakar et al. [9] investigated the effects of various dielectric media on near-dry EDM. The experiments showed that dielectric media with higher viscosity η and higher Prandtl number Pr gave more positive results than media with lower viscosity η. It can be explained by the three times higher material removal rate V_w of glycerin-air compared to oil-air and water-air as a dielectric. Previous publications on near-dry die-sinking EDM show insufficient knowledge about the process behavior, which does not allow a reliable industrial application.

This paper presents the results of the technological investigations on near-dry die-sinking EDM of CrCoMo dental bridges and the developed machining strategy. A water-air mixture is used as a dielectric, which is injected into the erosion zone via the copper tool electrode by a special flushing system. In order to increase the efficiency of the near-dry EDM process, the basic relationships between the process parameters capacitance C_L, discharge current i_e, average working voltage U, pulse duration t_i and pulse interval time t_0 are experimentally investigated using the design of experiments.

2. Experimental setup

The start hole drilling machine type ED 24 from Mitsubishi Electric Corporation, Tokyo, Japan is used to carry out technological research in the field of near-dry die-sinking EDM. The electrode flushing system, shown in Figure 1, is integrated into the machine system, as well as a bracket and two pressure regulators of type VRPA-CM-Q6-E from the company Festo SE & Co KG, Esslingen am Neckar, Germany, to regulate the input flushing pressure of the deionized water and compressed air.

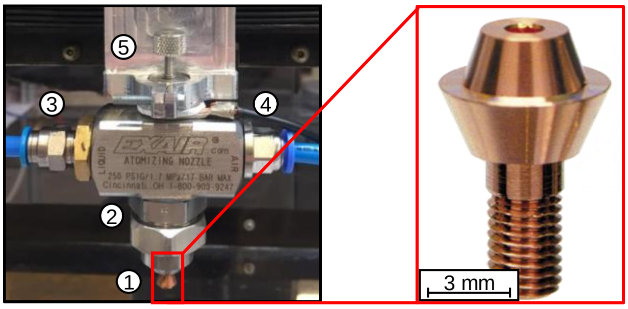


Figure 1. Electrode flushing system (1) tool electrode, (2) atomizer nozzle, (3) water inlet, (4) air inlet, (5) bracket

Subsequently, the internal mixing atomizer nozzle type An11020SS from EPUTEC Drucklufttechnik GmbH, Kaufering, Germany, allows pressure flushing with adjustable dielectric mixing ratio q through the form electrode. The dielectric mixture introduced as a spray mist consists of compressed air with an input flushing pressure of P_{in} = 7 MPa, deionized water with an input flushing pressure of P_{in} = 2.068 MPa and an electrical conductance of G = 10 µS/cm. The open circuit voltage is $\hat{u}_i$ = 71.5 V.The tool electrodes used are copper implant electrodes of type 82-0211 from SAE Dental Vertriebs GmbH, Bremerhaven, Germany. The water-air mixture is supplied to the erosion zone through a bore hole with a diameter of d = 1.6 mm in the implant electrode. A chrome-cobalt-molybdenum blank is used as a workpiece.

3. Analysis of the influence of the process parameters

The aim of the first series of experiments is to determine the main effects of the process parameters of the two target values arith. average roughness Ra and electrode wear rate V_E within the scope of statistical evaluation. For this purpose, a cavity is lowered into the workpiece with a processing time of t = 600 s. For the evaluation of the main effects of the five factors to be investigated, a critical experimental design is set up with resolution III. After determining the factorial 2^{5-2} experimental design, which was created with the help of the design of experiments methods, the experiments can be carried out with the process parameters shown in Table 1. This is done by means of three replications, each with a center point, in order to enable a statistical evaluation of the results. The metrological evaluation of the target parameter arith. average roughness Ra is performed on the optical 3D microscope G5 Infinite Focus from Alicona Imaging GmbH, Raaba, Austria.

Table 1. Process parameter settings of the first series of experiments

Process parameter	Unit	Setting		
		low (-)	medium (0)	high (+)
Capacitance C_L	nF	10	179	369
Average working voltage U	V	45	55	65
Discharge current i_e	A	15.6	16.2	16.9
Pulse duration t_i	µs	25	50	75
Puls interval time t_0	µs	5	10	15

The results of the main effect analysis are summarized in Table 2. The target values arith. average roughness and electrode wear rate are in the ranges of 1.91 µm ≤ Ra ≤ 3.27 µm and 0.37 mm³/min ≤ V_E ≤ 4.30 mm³/min, respectively. In each case, the color-coded arrows graphically represent the effect of the process parameter on the target value as a function of its significance in the confidence interval α. Aside from this, the change in the target value occurring when the setting is changed from the low level to the high level is indicated as a percentage. The arith. average roughness Ra increases by 23 % with medium significance when the setting of the discharge current i_e is changed. It also increases with medium significane by 21 % at the setting change of the pulse interval time t_0. The change of the setting of the pulse duration t_i leads to a low significant increase of the arith. average roughness Ra of 15 %. In contrast the setting change of the process parameters capacitance C_L and average working voltage U does not lead to any significant change in the target value arith. average roughness Ra.

The target value electrode wear rate V_E only increases if the setting of the capacitance C_L is changed with low significance by 75 %. In contrast the process parameters average working voltage U, discharge current i_e, pulse duration t_i and pulse interval time t_0 do not cause any significant change in the target value electrode wear rate V_E when the setting is changed.

Table 2. Comparison of the main effects of the process parameters

Process parameter	Arith. average roughness Ra		Electrode wear rate V_E	
Capacitance C_L	8 %	▲ (green)	75 %	▲ (yellow)
Average working voltage U	0 %	▲ (green)	3 %	▲ (green)
Discharge current i_e	23 %	▲ (red)	- 3 %	▲ (green)
Pulse duration t_i	15 %	▲ (yellow)	- 8 %	▲ (green)
Puls interval time t_0	21 %	▲ (red)	13 %	▲ (green)

Legend	
▲ (green)	no significance (α < 95 %)
▲ (yellow)	low significance (95 ≤ α < 99,9 %)
▲ (red)	high significance (99.9 % ≤ α)

The low significance of the capacitance C_L and the high significance of the discharge courent i_e, the pulse duration t_i and the puls interval time t_0 achieved for the target value arith. average roughness *Ra* differ from the effects of conventional EDM. This can be justified by the dielectric used or the mixing ratio of the spray.

The flow rate *Q* of the spray mist used is composed of 99.98 % air and 0.02 % deionized water, thus approaching dry EDM. In his investigations of near-dry and dry EDM, Tau [6] was also able to determine the discharge current i_e and the puls interval time t_0 as significant influencing variables of the target value arith. average roughness *Ra*. For a more detailed examination of the discharge processes, the prevailing current and voltage characteristics will be analyzed by means of an oscilloscope measurement as part of further experimental investigations.

4. Investigation of the influence of the mixing ratio of the spray mist

In order to analyze the influence of the mixing ratio *q* of the two dielectric media, the investigation of different flow rates *Q* is carried out in a second series of experiments. The previously varied process parameters are applied to a selected parameter combination, which achieves a minimum arith. average roughness *Ra* and an average electrode wear rate V_E. A surface roughness of $Ra \leq 2$ µm is required to prevent premature loss of prosthetic implants.

The flow rate *Q* of the spray mist or the mixing ratio *q* of the compressed air and deionized water, see Table 3, is then varied to eight levels based on the initial combination $C_L = 10$ nF, $U = 65$ V, $i_e = 15.6$ A, $t_i = 25$ µs, $t_0 = 15$ µs.

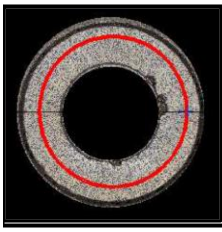
Table 3. Process parameter settings of the second series of experiments

Mixing ratio q		1	2	3	4
Compressed air flow rate Q_A	[ml/min]	63308	61642	54978	49980
Compressed air ratio q_A	[%]	99.98	99.94	99.51	98.94
Dielectric flow rate Q_D	[ml/min]	12	40	268	538
Dielectric ratio q_D	[%]	0.02	0.06	0.49	1.06

Three replications with a processing time of $t = 600$ s are performed in each case. The evaluation is carried out with respect to the arith. average roughness *Ra* and the electrode wear rate V_E.

It can be seen that with increasing flow rate *Q* and higher dielectric ratio q_D, small air bubbles are formed in the spray mist. These bubbles influence the surface structure formed during die-sinking EDM. Figure 2 shows the influence of the mixing ratio *q* of the spray mist on the surface structure. It is visually noticeable that at low dielectric ratio q_D, a surface structure with discharge craters typical for EDM is formed. As the flow rate *Q* increases, these craters are no longer visible, and instead a surface with molten discharge material is formed. Above a dielectric ratio of $q_D = 1$ %, a patterned surface occurs.

The evaluation of the arith. average roughness *Ra* and the electrode wear rate V_E shows that both target values are independent of the flow rate *Q* of the spray mist. For the surface roughness evaluation a measurement length of $l_m = 8.26$ mm with a profile width of $w_p = 0.05$ mm, shown in Figure 2, and a Lambda C filter of 0.8 mm is used. As shown in Figure 4, no clear trend can be identified. The arith. average roughness lies in a range of $0.6\ \mu m \leq Ra \leq 2.2\ \mu m$ for the investigated mixture ratios and scatters on average with a standard deviation of $s_D = 0.27$ around the arithmetic mean. The minimum arith. average roughness $Ra = 0.6$ µm is obtained for a compressed air ratio of $q_A = 98.94$ % and a dielectric ratio of $q_D = 1.06$ %. It therefore meets the surface roughness *Ra* of less than 2 µm required for the prevention of the premature loss of prosthetic implants. For the target value electrode wear rate V_E, a slight decreasing trend can be seen from the second to the fourth sample. With a mean standard deviation of $s_D = 0.02$, the electrode wear rate lies in a range of $0.6\ mm^3/min \leq V_E \leq 2.2\ mm^3/min$.



Process parameters and properties	
Capacitance C_L	10 nF
Average working voltage *U*	65 V
Discharge current i_e	15.6 A
Pulse duration t_i	25 µs
Puls interval time t_0	15 µs
Arith. average roughness *Ra*	0.6 µm

Figure 2. Machined cavitiy with a measurement length (red circle) for the evaluation of the arith. average roughness *Ra*

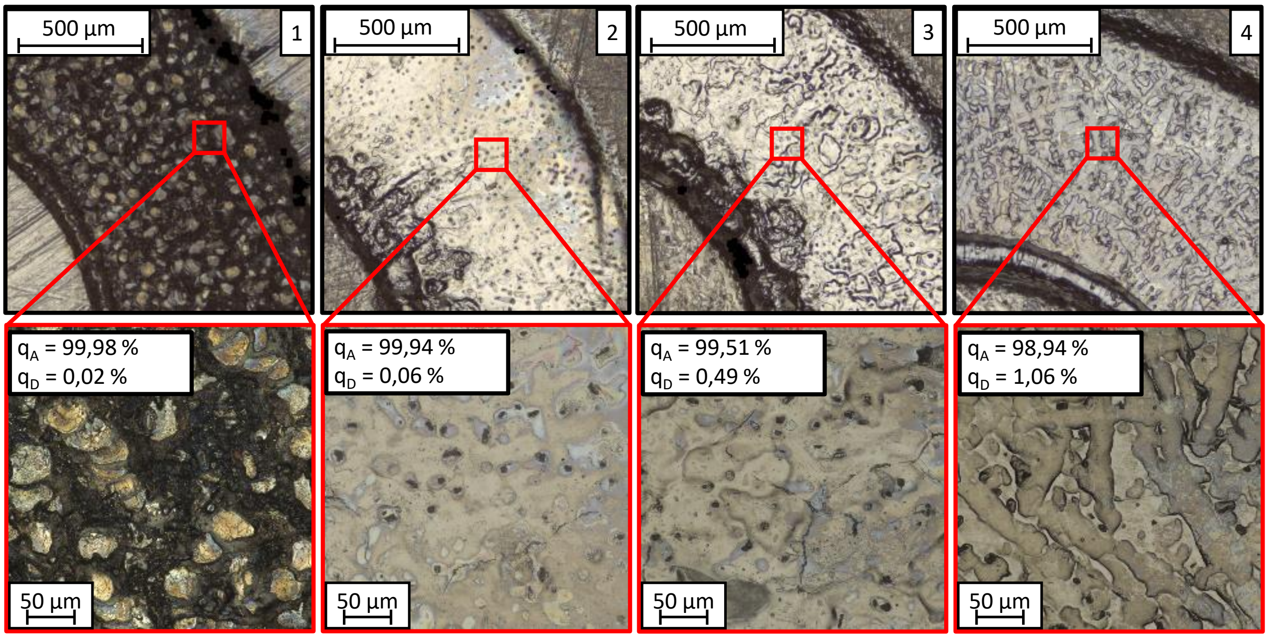


Figure 3. Influence of the mixing ratio *q* of the spray mist on the surface structure

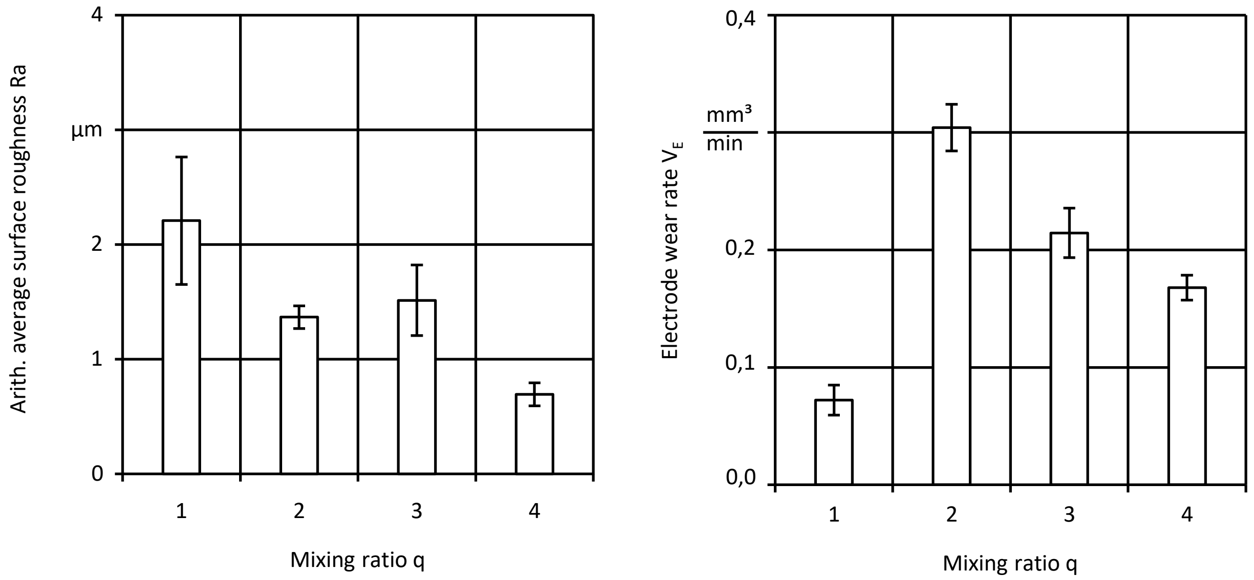


Figure 4. Mean and standard deviation of the target values arith. average surface roughness *Ra* and electrode wear rate V_E as a function of the mixing ratio *q*

The stated relationship between the surface structure obtained as a function of the mixing ratio *q* used and, related to this, the contamination of the working gap *s* is to be defined in further experimental investigations.

5. Summary and conclusion

This paper presents the results of experimental investigations on near-dry die-sinking EDM of CrCoMo dental implant structures. In the first series of experiments, the high significance of the discharge current i_e on the arith. average roughness *Ra* as well as the high influence of the capacitance C_L on the electrode wear rate V_E were demonstrated. Moreover, these process parameters, with their main effect, caused the largest change in the target values when their setting was changed from low to high level. Further experimental investigations on the current and voltage characteristics prevailing during discharge are necessary. In the second series of experiments, a reproducible surface structure, untypical for electroerosion machining, was obtained as a function of the flow rate *Q* as well as the composition of the spray mist used. It remains to be investigated what effect the resulting surfaces will have when used in dental technology, in particular how the bacteria react compared to conventional EDM surfaces.

Overall, the use of near-dry EDM technology, using a spray mist passed through the tool electrode, allows increased flexibility in the manufacturing process. Due to the independence from the dielectric basin, the developed machining strategy for dental implant structures can be integrated into hybrid machine systems.

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