An innovation approach of multiple discharging channels in EDM precision machining by a novel adaptive gap voltage control system

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Abstract. For decades, two issues, hard-to-improved machined surface roughness and low machining rate, have hindered the further developments of electrical discharge machining (EDM) Tool in precision manufacturing. In precision EDM, keeping a large gap distance is the only way for conventional EDM to obtain the integrity of a machined surface. However, the fact is large gap distances really prevented further improving machined surface quality and meanwhile lowered machining rate as well. Conversely, this paper tried to take small gap distances so that a discharging mechanism of generating multi-discharging channels from one pulse could be realized. The consequences were that both much greater improved machined surfaces and fast machining rates were obtained in addition to the more integrated machined surface than the conventional EDM did. To this end, a novel EDM adaptive control system was studied in this paper where arcing ratio was a control indicator and gap voltage was a control parameter. By presetting an arcing ratio expected value, arcing ratio can follow the value all the time by adapting gap voltage so that arcing pulses could not take place in the gap and thus the integrity of the machined surface can be obtained. By properly setting arcing ratio expected value, gap voltages could be adapted low enough with respect to arcing ratios so that multi-discharging channels from one pulse could be formed. Comparison experiments not only proved the effectiveness of the EDM adaptive control system but also demonstrated the feasibility of forming multi-discharging channels from one pulse in precision machining. Compared with conventional EDM, in addition to the more integrated machined surface had been obtained the surface roughness had been lowered almost 4 times and the machining rate improved 2.7 times. The significance of the study is that forming multi-discharging channels from one pulse displayed an innovative approach in precision EDM.

1. Introduction

Owing to its remarkable advantages of noncontact machining and machining conductive materials of any hardness, electrical discharge machining (EDM) has been used widely in aeronautics, textile industries, and mould and die industries, etc. In EDM, a series of pulse discharges occur in the discharging gap and discharging channel was formed in the gap. Each discharging makes the local
work-piece surface temperature rise quickly up to 10000°C-12000°C, which makes the material of discharging location melt and vaporize to generate erased craters on the work-piece surface. The dimension of the craters directly determines the quality of machined surface, the deeper and larger the craters are the higher the surface roughness (SR) is, and vice versa [1]. Therefore, in addition to the untouched machining, if the dimensions of the craters can be formed small enough, this kind of machining can surely be an alternative technique in precision manufacturing.

Some researchers have paid their attentions on how to obtain a fine surface machined by EDM. A Torres has verified that at low discharging energy conditions, the resulting craters were shallow and the surface had a homogeneous appearance by using copper electrodes [2-4]. Additionally, KM Patel used a Surface Roughness Prediction Model to analysis experiment variables thus proved a fact that low peak current and short pulse-on time can obtain low discharging energy [5]. By conducting Optimum Parametric experiments, MAR Khan [6] and S.H.Tomadi [7] proved that gap voltage was the most influential one among all the electrical parameters to SR with respect to experimental results by analysis of variance (ANOVA). Although it is confirmed that gap voltage has a biggest impact on surface roughness, the gap voltages in these researches are all fixed in machining processes. Therefore, it is necessary to develop a control system to timely regulate gap voltage for improving SR. For this purpose, Md. Ashikur Rahman Khan employed artificial neural network (ANN) approach in EDM of EN31 tool steel [8], Himadri Majumder using general regression neural network (GRNN) and MOORA-fuzzy-a MCDM approach for nitinol in WEDM [9] and PS Rao applied Hybrid Genetic Algorithm in WEDM [10]. Although these approaches have attained some effects, for EDM precision the machining mechanism should be further studied so as to obtain a feasible precision machining scheme.

In precision machining, the generation of arcing pulses can damage the integrity of machined surface. To obtain homogeneous machined surface, conventional EDM usually takes a fixed large gap voltage to ensure a large enough gap distance for avoiding arcing pulses which are detrimental to machined surface [11]. However, according to the discharging mechanism, it is clear that the large gap distances decelerate machining efficiency and in the meantime prevent further improvements of machined surface as well. That is because, normally a large gap distance only generate one discharging channel in one pulse discharging since the distance is so large compared with work-piece surface profile that a pulse can only discharge at a shortest distance. As a consequence, the whole energy of a discharging pulse was concentrated on one surface point leaving the produced crater unable to be further reduced.

On the contrary, the study in this paper showed that multi-discharging channels from one pulse can help to improve SR by generating smaller erased craters on the machined surface [12]. When gap distance is short enough to be comparable with work-piece surface profile meaning that they are almost in the same scale, one pulse may separate its energy in several locations on work-piece surface generating the so called multi-discharging channels from one pulse. Then the energy of a pulse is distributed into several discharging channels on the surface leaving smaller craters. It is observed that multi-discharging channels normally can only be obtained by shortening gap distance [13]. It is known that gap voltage linearly determines gap distance. Controlling gap voltages is equivalent to controlling gap distances. If technically arcing pulses are able to be avoided, and if the situation of multi-discharging channels from one pulse can be formed by lowering gap voltage, a fine machined surface and a fast machining efficiency can both be obtained.

For this purpose, this paper studied a novel EDM adaptive control system in which arcing ratio was a control indicator and gap voltage a control parameter to change gap distance. By setting a proper arcing ratio expected value, gap voltage could be adapted small enough to compel arcing ratio to pursue the value. In this way the situation of multi-discharging channels from one pulse can be formed from the small enough adapted gap voltages. Consequently, much better improved machined surfaces could be achieved in much shorter machining times than conventional EDM did. The study of forming multi-discharging channels from one pulse shows a distinctive approach from a new perspective of discharging mechanism and breaks through the inherent awareness of the precision machining by EDM in the past years. It is a new approach in EDM precision manufacturing.
2. A novel method of forming multiple discharging channels in precision machining

2.1. Mechanism analysis of forming multiple-discharging-channel

It is known that pulse discharging often occurs at a point where the gap distance is the shortest between electrode and work-piece. If the distance is large enough compared with work-piece surface profile measurements one pulse only forms one discharging channel as shown in Fig.1 (a). If the distance is short enough to be comparable with work-piece surface profile, multi-discharging channels from one pulse can be formed. The reason for that is as gap distance is short enough and when a pulse arrives the distances between several points on work-piece surface and the electrode can be broken down simultaneously by gap voltage which is the addition of pulse voltage and gap voltage. In this case, several discharging channels are simultaneously formed and many crests on surface are simultaneously erased shown in Fig.1 (b) leaving much smaller craters on the surface than a crater produced by only one discharging channel from one pulse. Therefore, two conditions must be satisfied in forming multi-discharging channels. One is the gap distance must be kept short enough so that the dielectric liquid at many points on the work-piece surface can be penetrated by gap voltage when a pulse arrives, the other is arcing pulses must be avoided.

![Figure 1](image)

Thus, two conditions must be satisfied for forming multi-discharging channels from one pulse.

**Condition 1:** arcing ratios must be controlled below a certain value throughout a process;

**Condition 2:** gap servo voltage must be small enough to gain short gap distances.

2.2. An mathematical model for EDM process

In fact, from a perspective of math, EDM process should belong to a deterministic and nonlinear process [14]. The arcing ratios in a machining process can be influenced by many factors. Meanwhile, because arcing ratio is an indicator reflecting the quality of machining states, a series of arcing ratios denote how a machining process experienced. Therefore, a timely-varied linear model can be built from it to approximate the nonlinear properties of EDM process. This model includes two portions, one is a definite portion and another one is a stochastic portion, as follows:

\[ A(q)y(t) = B(q)u(t) + C(q)e(t) \]  

In this equation \( q \) expresses a forward shift operator, \( A(q), B(q), C(q) \), polynomials of \( q \), \( A(q) = 1 + a_1q^{-1} + \cdots + a_nq^{-n}, B(q) = b_1q^{-1} + b_2q^{-2} + \cdots + b_mq^{-m}, C(q) = 1 + c_1q^{-1} + \cdots + c_nq^{-n} \). \( e(t) \) is a white noise with zero mean and variance \( \sigma^2 \) [15]. In the polynomials the parameters are estimated by recursive least-square algorithm [15].

\[ \hat{\theta}_t = \arg \min_{\theta} \sum_{k=1}^{t} \beta(t,k) [\delta_{arc}(t)(k) - \varphi^T(k)\theta]^2 \]  

In this equation \( \beta(t,k) = \lambda(t)t^{-k}, 0 \leq k \leq t - 1, \lambda(t) \) expresses a forgetting factor, and \( \beta(t,t) = 1 \). According to least-square algorithm, \( \theta = [a_1 \ldots a_n \ b_1 \ldots b_m \ c_1 \ldots c_n]^T \) can be recursively estimated [15], given by
\[
\begin{align*}
\dot{\theta}(t) &= \hat{\theta}(t-1) + L(t)[\delta_{arc}(t)(t) - \varphi^T(t)\theta(t-1)] \\
L(t) &= \frac{P(t-1)\varphi(t)}{\lambda(t) + \varphi^T(t)P(t-1)\varphi(t)} \\
P(t) &= \frac{1}{\lambda(t)}[P(t-1) - \frac{P(t-1)\varphi(t)\varphi^T(t)P(t-1)}{\lambda(t) + \varphi^T(t)P(t-1)\varphi(t)}]
\end{align*}
\] (3)

In this equation \( \varphi(t) \) can be named by forgetting factor. This model can be available for applications online [15].

2.3. Specific strategy

![Figure 2. A block diagram of adaptive control system for EDM process](image)

Based on the analyses above, Fig. 2 describes a schematic plan of the novel EDM adaptive control system. This system is made up of an inner loop and an outer loop. The arcing ratio \( \delta_{arc}(t) \) is fed into the outer loop to be a feedback. The arcing ratio expected value \( \delta_e \) is then fed into the inner loop and a control law is needed to calculate gap voltage \( u(t) \), so that arcing ratio \( \delta_{arc}(t) \) was compelled to pursue arcing ratio expected value \( \delta_e \) that has been used as an index to balance formation of multi-discharging channels from one pulse and machining rate. This paper took TP control law to fulfill the control strategy.

In general, a linear controller in a control system can be approximately expressed by [16]

\[
Ru(t) = T\sigma_{arc,e}(t) - S\sigma_{arc}(t)
\] (4)

In this equation \( R, S, T \) expresses polynomials of a shifting operator \( q \) [17]. When considering a two-step ahead of prediction, B polynomial should meet the requirement of \( B = B^+B^- \), follows by [17]

\[
q^d-1B^+C = AR + BS
\] (5)

In this equation \( d=2 \), \( R \) and \( S \) can be deduced by equating the equation. Then to introduce \( R \) and \( S \) into the Eq. (6) can obtain \( T \):

\[
\frac{BT}{AR+BS} = \frac{B_m}{A_m}
\]

\[
T = \frac{B_m(AR+BS)}{BA_m}
\] (7)

In this equation \( \frac{B_m}{A_m} \) denotes a transfer function in a desired model [17]. Then substituting \( u(t) \) in Eq. (1), the arcing ratio \( \sigma_{arc}(t) \) is expressed by

\[
\sigma_{arc}(t) = \frac{BT}{AR+BS}\sigma_{arc,e}(t) + \frac{RC}{AR+BS}e(t)
\] (8)

Then, according to the Eq. (4), TP control law can be written by

\[
u(t) = \left(\frac{AB_m}{BA_m} + \frac{SR_m}{RA_m}\right)\sigma_{arc,e}(t) - \frac{S}{R}\sigma_{arc}(t)
\] (9)

3. Verification experiments

On the basis of the analyses above, it is clear that the novel EDM adaptive control system in precision manufacturing can regulate gap voltages according to arcing ratios in machining well. Then,
it is necessary to clarify performances of the control system in integrity of machined surface, SR and machining efficiency.

**Table 1.** Machining parameter settings

| Voltage (V) | Peak current (A) | Pulse on time (µs) | Pulse off time (µs) | Electrode-discharging-time (Tool number) | Tool jump height (Tool number) |
|-------------|------------------|--------------------|--------------------|---------------------------------------|-------------------------------|
| 90          | 1                | 30                 | 42                 | 40 (1-256)                            | 4 (1-256)                     |

The gap servo voltage was set to 128 for conventional EDM, while gap servo voltage in adaptive EDM was a control variable. In the adaptive EDM, the arcing ratio expectation was set to 0.18.

**Table 2.** Experiments results

| Machining ways | Conventional EDM | Adaptive gap servo voltage EDM |
|----------------|------------------|-------------------------------|
| Ra (µm)        | 5.625            | 1.135                         |
| Machining time (min) | 120             | 43.2                          |

Experiments results were listed in table 2. It was seen that machining time from the adaptive controlled process was much shorter than that of conventional EDM process. Thus machining rate had been improved nearly 2.7 times. Meanwhile, from Table 4 it could be observed that surface roughness (SR) had also been decreased almost 4 times from conventional EDM. This is because while adapting gap voltage with respect to arcing ratios, gap distances could be maintained short enough to form the discharging pattern of multi-discharging channels from one pulse which led to the low SR.

**Figure 3.** Surface topographies at different magnification levels machined by (a), (c) conventional EDM, (b), (d) adaptive gap servo voltage EDM

Fig.3 shows the topographies of the machined surfaces by these two processes in precision machining. As shown in Fig.3 (a), it was easy to observe that there were many deep and large erased craters in the machined surface. Since the gap distance experimentally set in conventional EDM was too large for preventing the generation of arcing pulses, only one discharging channel could be formed at the highest crest from one discharging pulse in a local machined area. The consequence was that all the discharging energy of this pulse was consumed in the one crest, which makes the erased craters deep and large. Furthermore, because arcing ratios could not be controlled effectively in conventional EDM process, occasionally large numbers of arcing pulses took place in the gap to cause intensive discharging thus burns the machined surface shown in Fig.3 (c). Consequently, the integrity of machined surface was damaged. However, the machining mechanism is quite different in the process of adaptive gap voltage EDM. This novel control system substantially shortened gap distances to form multi-discharging channels from one pulse in the gap. Thus the discharging energy was dispersed and the erased craters formed were much smaller than that of conventional EDM, shown in Fig.3 (b). Therefore, surface roughness of adaptive gap voltage EDM is much lower than that of conventional EDM. Meanwhile, with the help of arcing ratio expectation, arcing ratios were controlled around the arcing ratio expectation to prohibit the generation of arcing pulses. The consequence of the machining was no burning mark in the machined surface, and a fine integrity of machined surface was obtained shown in Fig.3 (d).
4. Conclusion

1. Base on the analysis above and the conclusions, a mechanism of forming multi-discharging channels from one pulse was developed and a control strategy was build to achieve forming multi-discharging channels from one pulse.
2. A control law was deduced and theoretically proved its feasibility of driving arcing ratio to pursue an arcing ratio expected value.
3. A novel EDM gap voltage adaptive control system was developed and proved to be available throughout a machining process.
4. Comparison tests proved that the novel control system could maintain short enough gap distances to form multi-discharging channels from one pulse and obtained much improved surface in a short time from conventional EDM. Machining rate had been improved 2.7 times from conventional machining and SR almost 4 times from conventional machining. More importantly, no burning marks could be observed in adaptive EDM, which is impossible for conventional EDM, and the integrity of the machined surface had been realized.

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