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Wire Electrical Discharge Machining of Hardened Tool Steel: Effect of Process Parameters on Material Removal Rate and Surface Finish

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ABSTRACT

Wire electrical discharge machining is a non-traditional process capable of cutting hard, electrically conductive materials into intricate profiles that are difficult to produce by conventional methods. Its performance, however, depends strongly on the selection of electrical process parameters. This paper investigates the effect of pulse-on time, pulse-off time, and discharge currenton the material removal rate and surface finish during the wire electrical discharge machining of a hardened tool steel. Experiments were conducted at several parameter settings, and the material removal rate and surface roughness were measured. The results show that material removal rate increases with both pulse-on time and discharge current, as more energy is delivered per discharge, but that surface roughness deteriorates correspondingly because larger discharge craters are formed. Pulse-off time influences flushing and process stability. A trade-off therefore exists between productivity and surface quality, and the appropriate parameter selection depends on whether rough cutting or fine finishing is required. The study provides practical guidance for parameter selection in the wire electrical discharge machining of hardened steels.

KEYWORDS: *Wire Electrical Discharge Machining, Non-Traditional Machining, Material Removal Rate, Surface Roughness, Pulse-On Time, Discharge Current, Hardened Tool Steel*

INTRODUCTION

Wire electrical discharge machining removes material by a succession of controlled electrical discharges between a thin travelling wire electrode and the workpiece, both immersed in a dielectric fluid. Because cutting occurs through melting and vaporisation rather than mechanical force, the process can machine hard and brittle conductive materials regardless of their hardness, producing intricate profiles with fine tolerances (1, 9).

These capabilities make the process indispensable in tool and die manufacture, aerospace, and the machining of hardened steels and advanced alloys that are difficult to cut conventionally (1, 6). The performance of the process, however, is highly sensitive to the electrical parameters that govern the energy and timing of the discharges (3, 4).

This paper examines the influence of pulse-on time, pulse-off time, and discharge current on the material removal rate and surface finish during the wire electrical discharge machining of a hardened tool steel, with the aim of clarifying the trade-off between productivity and surface quality (5, 8).

LITERATURE REVIEW

The state of the art in wire electrical discharge machining has been reviewed comprehensively, covering the process mechanism, parameters, and developments in wire electrodes and control (1, 7). Foundational texts describe the physics of material removal by electrical discharge and the role of the dielectric and flushing (2, 9).

Numerous parametric studies, many employing designed experiments, have established that pulse-on time and discharge current are the dominant factors influencing material removal rate and surface roughness (3, 4, 5, 8). Investigations on difficult materials have confirmed these trends and explored the optimisation of competing responses (6).

PROCESS PARAMETERS IN WIRE ELECTRICAL DISCHARGE MACHINING

The literature identifies a set of electrical and control parameters as governing process performance (1, 3, 5). The principal parameters can be summarised as follows:

- Pulse-on time, which sets the duration of each discharge and the energy delivered.
- Pulse-off time, which allows dielectric recovery and influences flushing and stability.

- Discharge current, which governs the intensity of each spark.
- Wire tension and feed, which affect cutting accuracy and stability.
- Dielectric flushing pressure, which removes debris from the cutting gap.

RESEARCH GAP

Although the individual effects of electrical parameters are well documented, the simultaneous trade-off between material removal rate and surface finish for hardened tool steels is not always presented in an integrated and practical form for parameter selection.

This study addresses that gap by examining material removal rate and surface roughness together across a range of pulse-on times and discharge currents for a hardened tool steel.

OBJECTIVES

- To review the process parameters governing wire electrical discharge machining performance.
- To machine a hardened tool steel at varying pulse-on time, pulse-off time, and discharge current.
- To measure the material removal rate at each parameter setting.
- To measure the surface roughness of the machined surfaces.
- To characterise the trade-off between productivity and surface quality.

METHODOLOGY

Experiments were performed on a wire electrical discharge machine using a brass wire electrode to cut specimens of a hardened tool steel immersed in a dielectric fluid. The electrical parameters were varied in a controlled manner, and the material removal rate and surface roughness were measured for each setting (3, 4).

Workpiece, Electrode, and Machine

Specimens of a hardened tool steel were machined using a thin brass wire electrode on a wire electrical discharge machine with deionised water as the dielectric. Wire tension, wire feed, and flushing pressure were held constant so that the measured responses reflected the electrical parameters under study (1, 9).

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Table 1: Process Parameters and Levels Investigated

Parameter	Levels Investigated
Pulse-on time (µs)	4, 8, 12, 16, 20
Pulse-off time (µs)	6, 9, 12
Discharge current (A)	8, 12, 16
Wire electrode	Brass, 0.25 mm
Dielectric	Deionised water

Response Measurement

The material removal rate was determined from the cutting speed and the cross-sectional area of the kerf, and the surface roughness of the machined surface was measured with a stylus profilometer. Each measurement was averaged over repeated cuts to reduce scatter, and the parameters were varied one at a time about a central setting (3, 4, 5).

RESULTS AND FINDINGS

The variation of material removal rate with pulse-on time at three discharge currents is shown in Figure 1. The removal rate increased with both pulse-on time and discharge current, since each raises the energy delivered per discharge and therefore the volume of material melted and vaporised (3, 4).

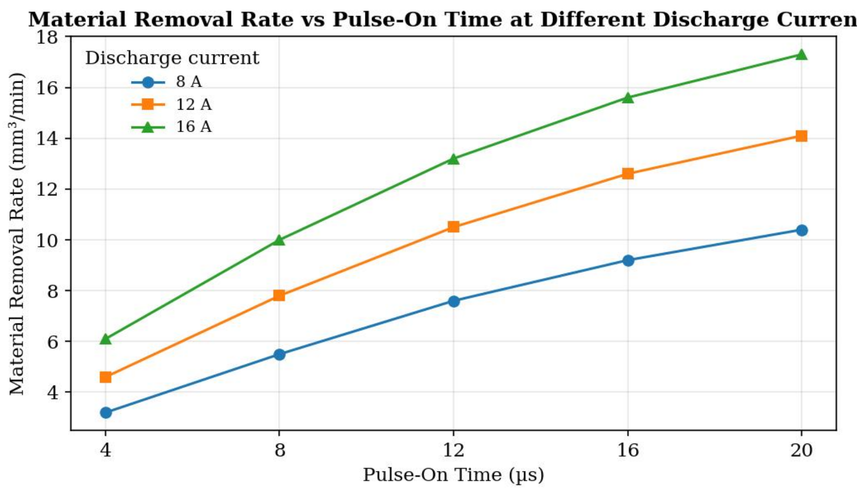

Figure 1: Material Removal Rate as a Function of Pulse-On Time at Different Discharge Currents

Table 2 lists the measured material removal rate and surface roughness at selected settings. The conditions that maximised the removal rate also produced the roughest surfaces, while gentler settings gave finer finishes at the cost of slower cutting, illustrating the trade-off between productivity and surface quality.

Table 2: Material Removal Rate and Surface Roughness at Selected Settings

Pulse-On Time (µs)	**Discharge Current (A)**	**MRR (mm^3/min)**	**Surface Roughness, Ra (µm)**
4	8	3.2	1.6
12	12	10.5	2.8
20	12	14.1	3.6
12	16	13.2	3.4
20	16	17.3	4.3

DISCUSSION

The results confirm that pulse-on time and discharge current are the dominant factors governing the material removal rate, consistent with the discharge-energy mechanism of the process (3, 4, 5). A longer pulse-on time and a higher current both increase the energy of each spark, melting and vaporising a larger volume of material and thereby raising the removal rate.

The same increase in discharge energy, however, forms larger and deeper craters on the machined surface, so that surface roughness deteriorates as the removal rate rises (4, 6). Pulse-off time plays a supporting role by allowing the dielectric to recover and debris to be flushed from the gap; an adequate pulse-off time is necessary for stable cutting, although it reduces the duty cycle and hence the removal rate (1, 8).

These observations reflect the fundamental trade-off between productivity and surface quality in electrical discharge machining (1, 7). In practice, high discharge energy is suited to rough cutting, where speed is paramount, while low energy is reserved for finishing passes that require a fine surface, often in a multi-cut strategy.

CONCLUSION

This study examined the effect of pulse-on time, pulse-off time, and discharge current on the material removal rate and surface finish during the wire electrical discharge machining of a hardened tool steel. Material removal rate increased with both pulse-on time and discharge current, while surface roughness deteriorated correspondingly as larger discharge craters were formed.

The findings confirm the inherent trade-off between productivity and surface quality in the process and provide practical guidance for parameter selection: high discharge energy for rough cutting and low energy for fine finishing. A multi-cut strategy combining both offers a means of achieving high productivity with a good final finish.

LIMITATIONS

- A single workpiece material and one wire electrode were used.
- Parameters were varied one at a time, so interactions were not fully resolved.
- Wire wear and wire-breakage behaviour were not quantified.
- Dimensional accuracy and kerf width were not the focus of this study.

FUTURE SCOPE

- Extension to other hard materials and advanced alloys.
- Use of designed experiments to capture parameter interactions.
- Investigation of multi-cut strategies for combined productivity and finish.
- Study of wire wear, kerf width, and dimensional accuracy.
- Application of multi-objective optimisation to balance the competing responses.

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