G Model
CIRPJ 420 No. of Pages 8

ARTICLE IN PRESS

CIRP Journal of Manufacturing Science and Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

CIRP Journal of Manufacturing Science and Technology

journal homepage: www.elsevier.com/locate/cirpj

Experimental investigation of energy distribution in continuous sinking EDM

K. Oßwald[a], S. Schneider[b,*], L. Hensgen[b], A. Klink[b], F. Klocke[b]

[a] Institute for Materials and Material Technologies, Pforzheim University, Pforzheim, Germany
[b] Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University, Aachen, Germany

ARTICLE INFO

Article history:
Available online xxx

Keywords:
EDM
Energy distribution
Temperature
Steel

ABSTRACT

Investigations into the fundamentals of the EDM process are often facing significant challenges due to the very small spatial and temporal scales in which it takes place. This also applies to the research on the distribution of the electrical energy of the discharges. This paper presents a novel method for the detailed experimental analysis of the energy distribution in continuous sinking EDM processes. For this purpose, sophisticated measurement methods for temperatures and electrical quantities were combined. Thus, the experimental setup was very close to realistic process conditions. The results of the obtained temperature profiles and the derived energy distribution are presented followed by variations of process parameters and a critical discussion to explain deviations.

Introduction

Literature review

Energy distribution is an important aspect of Electrical Discharge Machining (EDM) to specify the material loading. It influences the material removal from the workpiece and the tool electrode as well as the machining precision due to thermal expansion [1]. Energy distribution in EDM has been examined for decades, both theoretically and experimentally. Motoki and Hashiguchi [2] in a mostly theoretical study tried to explain different material removal rates at anodes and cathodes by various relations of electron and ion current densities. Shankar et al. [3] theoretically investigated the profile of the spark within the “Inter Electrode Gap” including energy distribution. On this scale more than 40% of the input energy is distributed into each of the electrodes and comparably little energy goes into the dielectric fluid.

Xia et al. have published different studies on the energy distribution for single discharges. A metal foil equipped with one [4,5] or several [1] thermocouple sensors serve as a workpiece. The energy distribution ratio was then determined iteratively by comparing the measured temperatures to calculated temperature curves. In their experiments roughly 40% of the energy is conducted into the anode and approx. 25% into the cathode when using copper as material for both electrodes [4] and approx. 20% into both electrodes when using steel electrodes [1]. In micro EDM Zahiruddin and Kunieda [6] used a similar setup to measure the effect of several pulses of $t_e = 0.2\ \mu s$. Comparing their results with Refs. [4] and [7] they suggest that the total energy distribution into the electrodes is decreasing with the discharge duration.

König et al. [8] introduced a method for the systematic determination of the energy distribution in a continuous EDM process using a symmetrical apparatus equipped with thermistor sensors within the dielectric fluid and the thermally isolated electrodes. They used this setup to examine the influence of pulse duration and current on the energy distribution. He also dealt with the transition from transient to steady state within a continuous EDM process. More recently Singh [9] adapted the method of Wertheim using different workpiece and tool electrode materials. A similar approach was used by Okada et al. [10]. For their study only one of the two electrodes was equipped with temperature sensors. In the experiments the energy distributed to the graphite tool electrode was about twice the energy distributed to the steel workpiece, independent of their polarity. However, the polarity showed a strong effect on the material removal rate for both tool and workpiece electrode.

Xia et al. [11] presented a study in Japanese language using tubular electrodes and a defined circulation of the dielectric fluid. The results were summarized in Ref. [12]. They found out that

* Corresponding author. Fax: +49 241 80 22293.
E-mail address: s.schneider@wzl.rwth-aachen.de (S. Schneider).

http://dx.doi.org/10.1016/j.cirpj.2017.04.006
1755-5817/© 2017 CIRP.

Please cite this article in press as: K. Oßwald, et al., Experimental investigation of energy distribution in continuous sinking EDM, NULL (2017), http://dx.doi.org/10.1016/j.cirpj.2017.04.006

Nomenclature

α Heat transfer coefficient W/m^2 K
ε Emissivity –
κ_X Thermal diffusivity (mm^2)/s
λ_X Thermal conductivity W/m K
ρ_X Density kg/m^3
A_X Area m^2
c_X Heat capacity J/(kg K)
d_X Diameter m
E_X Energy J
f Frequency Hz
$\Delta h_{f,X}$ Specific heat of fusion J/kg
ΔH_v Heat of evaporation J
$\dot{H}_X$ Enthalpy flow J/s
i_e, I_e Discharge current A
l_X Length m
m_X Mass kg
M_X Molar mass g/mol
n Quantity –
P_X Power W
Q_X Heat J
$\dot{Q}_X$ Heat flow W
r_X Radius m
$R_{s,X}$ Specific gas constant J/(kg K)
s Depth m
t Time s
t_0 Pause duration µs
t_e Pulse duration µs
t_{eros} Time between flushing jumps s
T_X Temperature °C, K
u_e Discharge voltage V
$\hat{u}_i$ Open circuit voltage V
V_X Volume m^3

Indices
DE Dielectric
E Electrodes
HL Heat loss
MR Material removal
RV Reservoir
EN Environment
TL Tool
WP Workpiece

about 48% of the process energy is dissipated to the tool electrode, 34% to the workpiece electrode and the remaining 18% is lost into the gap.

Energy distribution in EDM

As stated previously energy distribution in EDM process is a crucial issue. The input process energy E_{el} can be calculated as integral of voltage and current over time. Consequently, the discharge energy dissipating during one pulse can be determined by:

$$E_{el} = \int_{t=0}^{t_e} u_e \cdot i_e dt. \quad (1)$$

The exact distribution of this energy between tool, workpiece and dielectric fluid is still not resolved, especially regarding continuous processes. In transient consideration not the process energy but the process power has to be considered. However, it is common sense that the process power for single discharge and stationary thermal conditions during the process divides in five portions [12]. In each electrode a part of the distributed power (P_{TL}, P_{WP}) is lost to heat conduction into the electrode $\dot{Q}_{TL}$ and $\dot{Q}_{WP}$. Looking at material removal it is not sufficient to consider the heat flow but also the mass flows. Hence, enthalpy flows for material removal $\dot{H}_{MR}$ and tool wear $\dot{H}_{TL,wear}$ are taken into account. The last portion dissipates into the dielectric fluid $\dot{Q}_{DE}$ as depicted in Fig. 1.

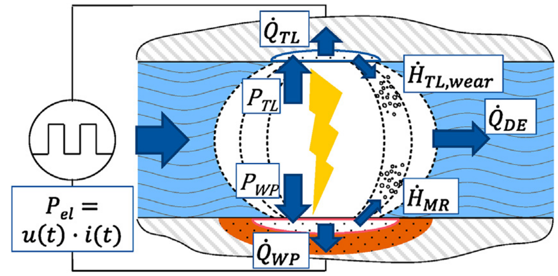

Fig. 1. Power distribution during EDM process.

In continuous process this distribution approach is supplemented with a convective heat flux from each electrode to the dielectric fluid $\dot{Q}_{E,DE}$ due to temperature gradients.

The purpose of this study is to show a new method of temperature measurement for continuous EDM process. First the geometry and the material properties of experimental setup will be determined. Together with the measured temperatures an energy distribution during a continuous process can be found. Finally, the influences of different parameter variations are analyzed and critically discussed.

Experimental setup

The experiments were conducted on a GFMS AgieCharmilles FORM 2000 sinking EDM machine. The erosion took place in an electrically insulated reservoir filled with V_{DE} = 700 ml of CH-based dielectric (Fig. 2). A cylindrical copper electrode with frontal area diameter of d_{TL} = 5 mm was used as a tool. Plates with the dimension of V_{WP} = 18 mm × 18 mm × 1 mm made of 42CrMo4 steel (1.7225) were used as specimens. For constant flushing conditions dielectric fluid was pumped continuously into the erosion zone. Since the reservoir was insulated the specimen was electrically contacted to the machine table.

The objective of this experiment was to quantify the thermal energy flows during continuous EDM process. For this purpose the temperatures of the specimen, tool electrode and the surrounding dielectric fluid had to be recorded. In order to measure the temperature of the workpiece a high speed thermographic camera FLIR X6580sc is used. The specimen was integrated in the reservoir wall. Thus, only one side was in touch with the dielectric and the outer side was visible (cp. Fig. 2). The camera recorded the heat radiation emitted by the visible side of the machined specimen and convert it via Planck's law to a surface temperature. For calibration and verification of the thermographically measured temperatures an additional thermocouple is placed on the specimen. The specimens were painted with a special heat resistant black lacquer. Thus, it can be assumed that the specimens had an emissivity of $\varepsilon \approx 1$ and emitted black body radiation. The temperature of the dielectric fluid was measured by another thermocouple. In order to calculate the heat flux into the tool electrode it was necessary to implement three thermocouples at intervals of l = 5 mm starting 5 mm from the frontal surface. All temperature signals were recorded at f = 100 Hz, whereupon the discharge frequencies were