CIRP Annals - Manufacturing Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

# Deformation of thin graphite electrodes with high aspect ratio during sinking electrical discharge machining

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ARTICLE INFO

*Keywords:*
Electrical discharge machining (EDM)
Modelling
Dynamic mechanical analysis (DMA)

ABSTRACT

In sinking electrical discharge machining (SEDM) use of thin graphite electrodes with high aspect ratio sporadically results in geometrical errors. Mechanical and thermal loads introduced due to jump flushing movements and multiple discharges may exceed critical material properties of graphite. In this paper, deformation effects are modelled by a three step simulation strategy considering discharge distribution, heat evolution and fluid structure interactions (FSI). Mechanical and thermal properties of graphite are characterized with focus on dynamic mechanical thermal analysis (DMA) and implemented into the multiphysics simulation model. Finally, characteristic curves are derived based on simulations in order to avoid critical deformations.

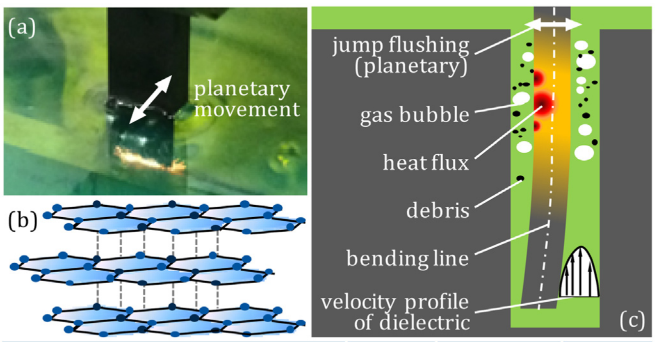


## 1. Introduction

Sinking electrical discharge machining (SEDM) is oftentimes used when cavities with sharp edges and high aspect ratios have to be manufactured in hard-to-machine materials. Major industries with typical applications are die and mould making [1] and aerospace sector [2]. When machining mentioned cavities modern sinking EDM machine tools generally use flushing by motion arising from jerky movements of machine tool axis [1–3]. Especially in micromachining or for finishing operations planetary movement of the electrodes leads to significantly increased process quality in terms of stability, material removal rate and reduction of wear [4,5]. Due to its well suited physical properties in terms of thermal and electrical conductivity as well as its good machinability, nowadays, graphite is the predominant electrode material in common use, cp. Fig. 1. Crystalline graphite has hexagonal structure consisting of different (basal) planes of graphene. Thus, on a crystal level high anisotropy can be explained regarding the physical properties. However, modern graphite grades for EDM applications are polycrystalline materials manufactured by isostatic forming resulting in randomly oriented crystals, pores and micro-cracks and therefore in isotropic physical material properties [6].

Besides developments in generator techniques during the last decades a lot of effort was made to increase machining efficiency by improved jump flushing movements of SEDM machine tools. Hereby, first of all jerk of machining axis was increased in order to reduce non-productive time. Since latest machine tool developments these improvements sporadically resulted in geometrical errors of manufactured workpieces being out of their respective tolerances. Inadequateness in processing thin graphite electrodes by milling or wire EDM, e.g. shown by Kawakami and Kunieda, could be sorted out just as potential quality defects regarding the graphite material itself [3,7].

In EDM comprehensive work has been done in analysing gap conditions directly related to the electrical discharge [2,8]. In that course research was predominantly done on plasma temperature and pressure [5], gas bubble formation and debris distribution [9] as well as energy distribution [10–14]. Besides, for the first time Garzón investigated the deflection of thin graphite electrodes due




| (d) position to basal level | \|\| | ⊥ | \|\| / ⊥ |
|---|---|---|---|
| electrical cond. κ / (S/mm) | 2,200 | 0.25 – 0.5 | > 4,000 |
| therm. cond. λ / (W/(cm·K)) | 10 – 15 | 0.02 – 0.04 | > 250 |
| therm. exp. coeff. α / (μm/(m·K)) | -1.5 | +28.3 | – |
| Young´s modulus E / GPa | 1,060 | 36.5 | ≈ 30 |

**Fig. 1.** Thin graphite electrode (a), hexagonal structure of graphite (b), schematic overview of mechanical and thermal loads (c) and physical properties parallel and perpendicular to basal plane of graphite (d).

http://dx.doi.org/10.1016/j.cirp.2017.04.139
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to continuous discharge forces. Although Garzón could show that unfavourable discharge frequencies could lead to machining deviations the author stated that hydrodynamic forces on thin electrodes due to flushing are magnitudes higher than the ones caused by discharges [5].

Nevertheless, in all those studies electrode material was supposed to be ideal stiff. For the first time, Klocke et al. analysed bending of thin graphite electrodes with high aspect ratio by high-speed camera recordings and fluid-structure interaction (FSI) simulations. They stated that against the prevailing opinion of graphite showing a pure brittle material behaviour, named class of electrodes deformed by reactive flushing forces. In a first approach, authors neglected any heating effects due to multiple discharges acting on the electrode, which may even intensify those effects [15].

In this paper, temperature effects due to multiple discharges extend the list of reasons for the deformation of thin graphite electrodes in sinking EDM. Therefore, a multi-level simulation model is introduced consisting of discharge distribution, heat-transfer and fluid-structure interaction (FSI). Extensive studies concerning temperature dependent material behaviour of graphite with focus on dynamic mechanical analysis (DMA) are presented and serve as input for the simulation model.

## 2. Experimental

From material manufacturers, physical properties of graphite are usually only given at room temperature. Heat transfer due to multiple discharges acting on graphite electrodes during EDM changes these properties. Therefore, focus of experimental investigations was on characterization of graphite material at elevated temperatures. Experiments can further be divided into measurements concerning thermal, mechanical and electric parameters. The latter property was only characterized in terms of the electrical conductivity.

Table 1 gives an overview of the derived physical properties along with the respective testing method according to DIN standard as well as values for graphite grade SGL R8710 at room temperature. With the equipment available thermal conductivity, thermal expansion and specific electrical resistivity could be measured in a temperature range between 20–2500 °C. In terms of the mechanical behaviour, tensile and flexural strength tests were carried out for a temperature range between room temperature and 1900 °C. From these measurements Young's modulus was derived as a function of temperature.

Due to the fact that testing of mechanical properties in terms of tensile or flexural strength are usually destructive, potential anelastic or viscoelastic effects cannot be observed appropriately by these methods. Therefore, stress–strain behaviour of EDM graphite was examined at finite stress and strain amplitudes by dynamic mechanical analyses (DMA). In general, the energy loss in a solid subjected to cyclic stress is known as damping or internal friction. Corresponding experiments were done on NETZSCH DMA 242 E Artemis. Graphite specimen's dimensions were $20 \times 10 \times 2$ mm and frequencies, strain-amplitudes and temperature range were chosen and varied with regard to potential loadings in typical EDM processes, cp. Fig. 2.

The DMA was carried out at the Fraunhofer Institute for Material Mechanics (IMM) in Freiburg Germany. During DMA, sample is subjected to a sinusoidal mechanical load $\sigma(t)$ while

**Table 1**
Physical properties, testing methods and properties of graphite SGL R8710 at room temperature.

| Physical property | DIN standard | R8710 @20 °C |
|---|---|---|
| Therm. conductivity $\lambda$ | 51908 | 99 W/(m K) |
| Therm. expansion $\alpha$ | 51909 | 4.2 ($\mu$m/m K) |
| Flexural strength $\sigma_B$ | IEC 413/501 | 92 MPa |
| Young's modulus $E_B$ | 51915 | 9.3 GPa |
| Spec. elect. resistivity $\rho$ | IEC 413/402 | 14 $\mu\Omega$ m |

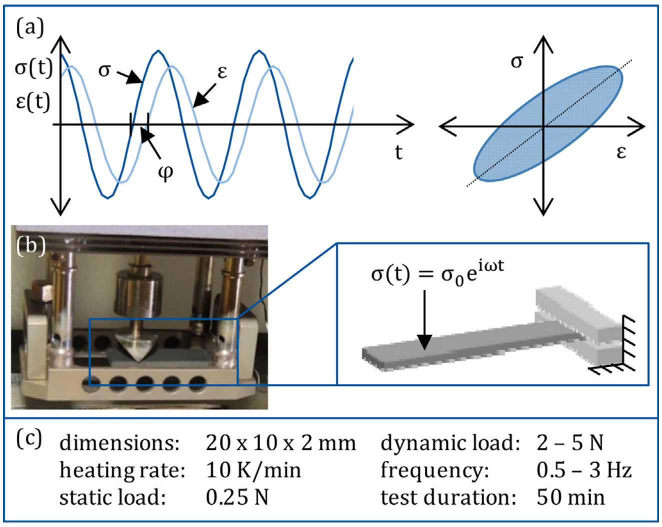


**Fig. 2.** Physical background (a) experimental set up (b) and parameters (c) of dynamic mechanical analysis (DMA).

constantly increasing temperature. In contrast to horizontal axis movement in planetary erosion (cp. Fig. 1(a) and (c)) the load in DMA is applied vertically (cp. Fig. 2(b)). Stress and strain amplitude $\varepsilon(t)$ as well as phase shift $\varphi$ between two signals are continuously recorded. Material's damping can be derived from the phase shift. Thus, a purely elastic material is characterized by the absence of a phase shift. The larger anelastic or viscoplastic part of the deformation becomes, the stronger the internal friction.

## 3. Modelling

The highly complex EDM process demands for consideration of different physical phenomena and thus does not allow a fully coupled approach [8]. For modelling the bending of thin graphite electrodes the following strategy was chosen, cp. Fig. 3.

First, finite number of possible discharge distribution is determined using a Monte Carlo simulation. Subsequently, the discharge distribution with the highest concentration of discharges in the upper region of the electrode is selected (A) to determine a kind of worst-case scenario. This distribution is then used to simulate the heating of the electrode in the erosion phase (B). Resulting temperature distribution enables the specification of the temperature-dependent material properties of the graphite electrode for the subsequent FSI simulation of the jump planetary movement (C). Finally, permanent deformation of the electrode can be determined from the heat simulation and the elastic deformation which was determined by the FSI simulation. In the following paragraphs the assumptions for the Monte-Carlo

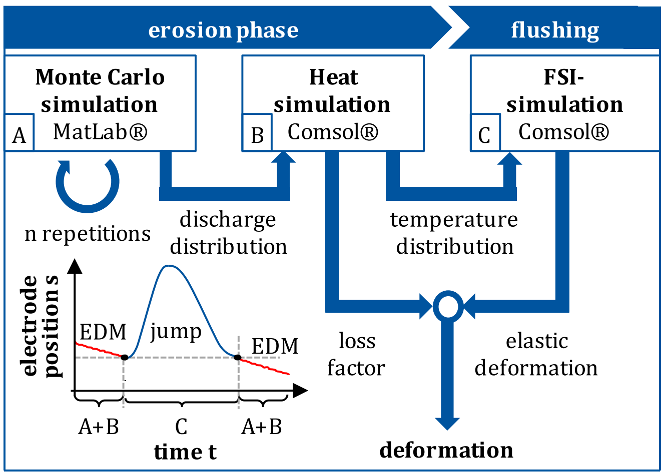


**Fig. 3.** Simulation steps for the determination of lasting electrode deformation.