A Mechanical Model of Diamond Wire Sawing of Steel Structures

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Abstract. Wire sawing with diamond tools is a highly flexible cut-off grinding process with regard to machinable component structure and composition. Nowadays, it is deployed in many fields of application e.g. the dismantling of nuclear or industrial plants. Here, steel has to be cut which results in lower productivity and tool life compared to the conventional processing of natural stone. To ensure a properly designed process the mechanical and thermal tool loads have to be known in advance. This paper presents an analytical model that predicts the mechanical load as a function of the process parameters.

Introduction

Initially, wire sawing was introduced in the natural stone sector to extract blocks in open-cast mines. In the beginning, loose abrasive grains were used in a lapping process. In the 1970s, a wire sawing tool with fixed diamond grains was developed, replacing lapping by grinding with geometrically indeterminated abrasive cutting edges [1]. Wire sawing offers an unlimited cutting depth and length and is flexible concerning the machinable workpiece material composition. Compared to other cut-off processes, the machine technology operates with minimum space requirements and causes only small set-up efforts and investment costs. Because of these advantages, wire sawing is nowadays frequently used in the construction industry to cut off concrete, reinforced concrete and metal [2,3,4,5]. A particular field of application is the dismantling of nuclear power plants where specific challenges arise. A nuclear power plant has to be decommissioned and dismantled when it has reached its designated operating time or due to political or economical decisions. The International Energy Agency estimates that 200 nuclear power plants worldwide have to be decommissioned until 2040 [6]. A pressurized water reactor is the most frequently deployed reactor type. Here, 170,000 t of concrete and 35,000 t of steel have to be disassembled for each plant [7,8]. Diamond wire sawing of steel is generally applicable but results in lower productivity and tool life compared to the processing of natural stone or concrete (Fig. 1) [2].

![Figure 1: Specific removal rate and tool life for different materials [2]](image-url)
Even compared to cutting-off concrete with 4 % steel reinforcement the specific removal rate and the tool life in terms of the specific cutting surface (achieved cut-off surface per m tool) are significantly lower by on average 97 % and 93 %, respectively. It is well established that diamond is not suitable to process steel due to chemical diffusion. Nevertheless, CBN grains malfunction in wire sawing process due to their poor mechanical resistance compared to diamonds. Furthermore, chemical diffusion of the big diamond grains was not observed during experiments [2]. Besides material and tool properties the wear behavior is influenced by the mechanical and thermal tool loads during grinding. If these tool loads can be predicted depending on the process parameters in advance, the cut-off process can be designed properly to increase the tool life and the productivity. So far, no model for the diamond wire sawing has been introduced. To close this gap, this paper presents an analytical mechanical model predicting the process forces as a function of the process parameters.

Principles of the diamond wire sawing process

A diamond wire sawing tool consists of grinding segments with fixed diamonds that are mounted on a carrier wire at defined distances. The process parameters are the wire pretension force $F_V$, the feedrate $v_f$ and the cutting speed $v_c$. The wire pretension ensures a sufficient traction between the drive pulley and the wire and provides the cutting pressure. The vectorial sum of feedrate and cutting speed is the effective speed required for the chip formation. In order for the diamond grains to penetrate the material, the grinding process demands a normal force $F_n$ against the direction of the feedrate and thus radial to the wire axis. In contrast to other grinding processes, this normal force is not supplied directly by a stiff tool, but indirectly by the wire pretension. Due to the negligible flexural rigidity of a wire sawing tool, forces cannot be absorbed in radial direction of the wire. As a consequence, the wire has to be deflected to transmit the force in axial direction into the wire. This deflection leads to a deviation of target ($s_f, v_f$) and actual ($s_{f\text{ eff}}, v_{f\text{ eff}}$) feed and velocity values (Fig.2).

The deflection $s_\Delta$ denominates the difference between the distance travelled by the feed pulleys $s_f$ and the distance $s_{f\text{ eff}}$ that the diamond wire penetrates into the workpiece:

$$s_\Delta = s_f - s_{f\text{ eff}}$$  \hspace{1cm} (1)

The deflection is not constant during a single grinding operation. It depends on the deviation of the feedrate $v_f = ds_f / dt$ and the effective feedrate $v_{f\text{ eff}} = ds_{f\text{ eff}} / dt$. In an infinitesimal time interval $dt$ the change of the wire deflection is:

$$ds_\Delta = ds_f - ds_{f\text{ eff}} = (v_f - v_{f\text{ eff}}) \cdot dt$$  \hspace{1cm} (2)
From this equation, the time derivative of the wire deflection can be deduced. It is the velocity of the deflection change in an infinitesimal timespan $dt$

$$\frac{ds_{\Delta}}{dt} = v_{f} - v_{f_{\text{eff}}}
\tag{3}$$

It is expected that the mechanical and thermal loads are a function of the effective feedrate $v_{f_{\text{eff}}}$. If the wire deflection could be predicted as a function of the process parameters and the grinding time the process loads can be concluded. Therefore, the subject of the next section is the modeling of the wire deflection.

**Analogous mechanical model**

Fig. 3 depicts a sketch of the wire sawing process and the derived analogous model. The following model assumptions are made:

- The wire sawing tool is modeled as ideal string withou t mass, elongation or flexural rigidity. The actual weight force of the considered wire unit is negligible small in comparison to the process forces. It is assumed that the real elongation can be neglected. Because the diameter of the wire is small compared to its length, the assumption of no flexural rigidity is valid as well.
- The axial wire force is equal to the pretension force $F_{V}$. A pneumatic linear drive generates the pretension force and maintains this force constant.
- The workpiece is positioned equidistantly between the feed pulleys.
- The line load $q(x)$ remains constant over the workpiece length $l_{WS}$ and can be reduced to the resulting normal force $F_{n} = l_{WS} q$. The cutting length $l_{c}$ increases with a longer wire bow inside the workpiece. For the experimental set up presented here, this increase leads to deviations of the cutting length of only 2 - 5 %. Hence, the assumption is reasonable that the influence of the wire bow inside the workpiece is of minor importance.
- The process parameters $v_{c}$, $v_{f}$ and $F_{V}$ are not varied during one grinding operation.
- The grinding force ratio $\mu = F_{t} / F_{n}$ and the specific grinding energy $e_{c}$ are constant over time. In fact, $\mu$ and $e_{c}$ change slightly during one grinding process. This variance is neglected to keep the model manageable.
The equilibrium of forces in z-direction leads to the following equation for the normal force:

\[ F_n = 2 \cdot F_V \cdot \sin \alpha = 2 \cdot F_V \cdot \frac{s_{\Delta}}{\sqrt{\left(\frac{l_{fs} - l_{ws}}{2}\right)^2 + s_{\Delta}^2}} \]  

(4)

For large free wire lengths \( l_{fs} - l_{ws} \) and compared to this small deflections \( s_{\Delta} \), \( (l_{fs} - l_{ws}/2)^2 \gg s_{\Delta}^2 \). Hence, Eq. 4 can be approximated with sufficient accuracy by a linear function:

\[ F_n \approx \frac{4F_V}{l_{fs} - l_{ws}} \cdot s_{\Delta} \]  

(5)

Using the grinding force ratio \( \mu = F_t / F_n \) the tangential force is:

\[ F_t \approx \mu \cdot \frac{4F_V}{l_{fs} - l_{ws}} \cdot s_{\Delta} \]  

(6)

**Derivation of a process force model**

Eq. 5 and 6 show that a change of the wire deflection leads to a change of normal and tangential grinding forces.

The specific grinding energy \( e_c \) is the energy expended to remove a unit material volume during grinding. It depends on the properties of the material to cut, the tool and the grinding parameters. In terms of the cutting power \( P_c \) and the material removal rate \( Q_w \) the specific energy in wire sawing is:

\[ e_c = \frac{P_c}{Q_w} = \frac{F_t \cdot v_c}{d_s \cdot l_c \cdot v_{teff}} \]  

(7)

Here, \( d_s \) is the diameter of a grinding segment and \( l_c \) is the grinding length. With Eq. 6 and 7 the effective feedrate \( v_{teff} \) is given by:

\[ v_{teff} = \frac{\mu \cdot 4F_V \cdot v_c}{d_s \cdot l_c \cdot (l_{fs} - l_{ws})} \cdot s_{\Delta} = k \cdot s_{\Delta} \]  

with \( k = \frac{\mu \cdot 4F_V \cdot v_c}{d_s \cdot l_c \cdot (l_{fs} - l_{ws})} \)  

(8)

The constant \( k \) includes all factors that are constant over time according to the model assumptions. Substituting the effective feedrate in Eq. 3, the wire deflection can be derived as a linear first order differential equation:

\[ \frac{d s_{\Delta}}{dt} + k \cdot s_{\Delta} = v_t \]  

(9)

At the beginning of each grinding the wire is not deflected, i.e. \( s_{\Delta}(t = 0) = 0 \). With this initial value the solution of the differential equation is:

\[ s_{\Delta}(t) = \frac{v_t}{k} \cdot (1 - e^{-k \cdot t}) \]  

(10)

With Eq. 5 and 6, the progress of the normal and tangential force with time are represented by the following equations:

\[ F_n(t) = \frac{e_c}{\mu} \cdot d_s \cdot l_c \cdot \frac{v_t}{v_c} \cdot (1 - e^{-k \cdot t}) \]  

(11)

\[ F_t(t) = e_c \cdot d_s \cdot l_c \cdot \frac{v_t}{v_c} \cdot (1 - e^{-k \cdot t}) \]  

(12)

In general, tool wear in case of flattened grains will lead to higher process forces. This fact is implemented indirectly into the model because the specific grinding energy \( e_c \) and the grinding force ratio depend on the tool wear. In Fig. 4, calculated forces according to Eq. 11 and 12 are...
depicted with the corresponding experimental results. The experimental investigations were conducted on a prototypical wire saw that operates in plunging mode as shown in Fig. 2. The feed pulleys are moved path driven. The pretension force is kept constant by a pneumatic cylinder. In the experiments a Husqvarna wire sawing tool C1000 was used to cut-off solid steel S355JR with a ferritic-perlitic structure. $n_s = 44$ grinding segments per meter tool are mounted on a carrier wire leading to a segmentation of $\lambda = 0.22$. This implies that 22% of the wire surface are grinding segments. $\mu$ and $e_c$ were determined during the experiments. It can be seen that the derived model is capable to predict the measured values almost perfectly. Both measured force progressions correlate with the modeled forces with a coefficient of determination of $R^2 = 0.99$.

Both forces approach a steady state for $t \rightarrow \infty$. In this stationary state, the wire deflection is constant and the effective feedrate is equal to the feedrate. The grinding forces in steady state are:

$$F_n = \lim_{t \rightarrow \infty} F_n(t) = \frac{e_c}{\mu} \cdot d_s \cdot l_c \cdot \frac{v_f}{v_c}$$

$$F_t = \lim_{t \rightarrow \infty} F_t(t) = e_c \cdot d_s \cdot l_c \cdot \frac{v_f}{v_c}$$

Due to the properties of the exponential function, this steady state will never be reached in experiments. The deviation $\varepsilon$ of the actual grinding forces and the theoretical in the steady state is given by:

$$\varepsilon(t) = \frac{F_n - F_n(t)}{F_n} = \frac{F_t - F_t(t)}{F_t} = e^{-k \cdot t}$$

With this deviation, the measured force at a specific time can be used to predict the stationary force. The time to reach a certain deviation is:

$$t = \frac{-\ln(\varepsilon)}{k} = -\ln(\varepsilon) \cdot \frac{d_s l_c (l_f - l_{ws})}{4 F_v \n_c}$$

The time to reach deviations of 0.1, 0.05 and 0.01 are depicted in Fig. 4 for the shown process. The derived model reveals some qualitative insights into the wire sawing process:

- The wire deflection and the process forces approach a steady state.
- The progression of the wire deflection and the grinding forces depend on the grinding time and a constant $k$. $k$ is a function of the process parameters and geometrical properties of machine, workpiece and tool. Higher values of $k$ lead to a faster increase of the process forces.
• The process forces are directly influenced by the feedrate $v_f$. With a higher feedrate more material has to be removed per time. This causes higher process forces and an increasing wire deflection.
• An increase in the cutting speed $v_c$ leads to lower process forces and wire deflections. It is assumed that higher temperatures in the contact zone result from increased cutting speeds. Hence the resistance of the material to be removed is lower.
• The pretension force $F_V$ has no influence on the process forces in the stationary state. Higher pretension forces cause lower wire deflections and a faster increase of the process forces.
• The quantitative values of the process forces are a function of the specific grinding energy $e_c$ and the grinding force ratio $\mu$. From theory, it can be expected that the specific grinding energy is a function of the process parameters. Their values in dependency on the process, machine and workpiece properties have to be determined experimentally.

Summary and outlook
In this paper, a mechanical model of the wire sawing process has been derived analytically. The presented model is capable of predicting the mechanical tool load as a function of the process parameters and the grinding time. The accordance of modeled and measured normal and tangential forces was shown. Hereby, the wire sawing process can be designed properly and adapted to a specific cut-off operation.

In further research activities, the thermal loads and the tool wear will be investigated. The dependency of the specific grinding energy on the process parameters as well as tool and material properties will be determined. The model will be extended to tool specifications and non-solid structures to be cut. By this, a model of the wire sawing of steel will be derived that is valid over a wide range of applications.

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