Influence of diamond wire pretension on process behaviour

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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. Therefore, it is nowadays not only used in the processing of natural stone, but also increasingly deployed on dismantling of nuclear or industrial plants. In this field of application, concrete, reinforced concrete and steel have to be cut. In particular, the processing of reinforcements and steel structures results in higher process forces compared to the machining of natural stone or concrete. Consequently, the diamond wire is deflected leading to decreased cutting performance in terms of the material removal rate. To overcome these challenges, the diamond wire can be pretensioned which directly affects the stiffness of the tool. Thereby, the deflection of the diamond wire can be reduced and the material removal rate can be increased.

This paper presents initial results concerning the influence of the wire pretension on the process behaviour of a diamond wire when cutting steel S355JR. For these investigations, the wire pretension was varied in a range of 300 N up to 2000 N. For the evaluation of the process behaviour, resulting process forces, cutting power, wire deflection and surface removal rate were analysed.

KEYWORDS

cut-off grinding, wire sawing, wire pretension, diamond tools, dismantling

INTRODUCTION

Initially, wire sawing was introduced in the processing of natural stone [1]. Due to its unlimited cutting depth, wire sawing allows the exploitation of blocks of huge dimensions. Based on the high flexibility concerning the machinable component structure and composition, wire sawing is frequently used in the construction industry to cut-off concrete, reinforced concrete or steel [2,3,4]. Compared to competitive cut-off processes, the machines used for wire sawing are small, easy to set up and inexpensive (Fig. 1).

Because of the mentioned advantages, wire sawing is nowadays used in the dismantling of nuclear or industrial plants [5,6]. The number of dismantling activities for nuclear power plants is going to grow significantly in the future. Many plants have reached their designated operating time or are going to be decommissioned due to political decisions. In Germany alone, 9 nuclear facilities for commercial power generation have to be decommissioned until 2022. Together with 23 already decommissioned plants they have to be dismantled afterwards [7]. In the dismantling of nuclear power plants, specific challenges have to be taken into account. Large components consisting of different materials have to be cut-off. Depending on the size of the reactor, 200,000 to 400,000 t of concrete have to be removed. In addition, several 10,000 t of reinforcement steel and steel structures have to be disassembled [6,8].

The cutting of steel results in higher process forces that lead to a deflection of the diamond wire. As a consequence, the material removal rate is reduced. In this paper the influence of the wire pretension on the process behaviour is investigated. Therefore, steel S355JR was cut and the process forces, power consumptions, wire deflections and surface removal rates were measured.

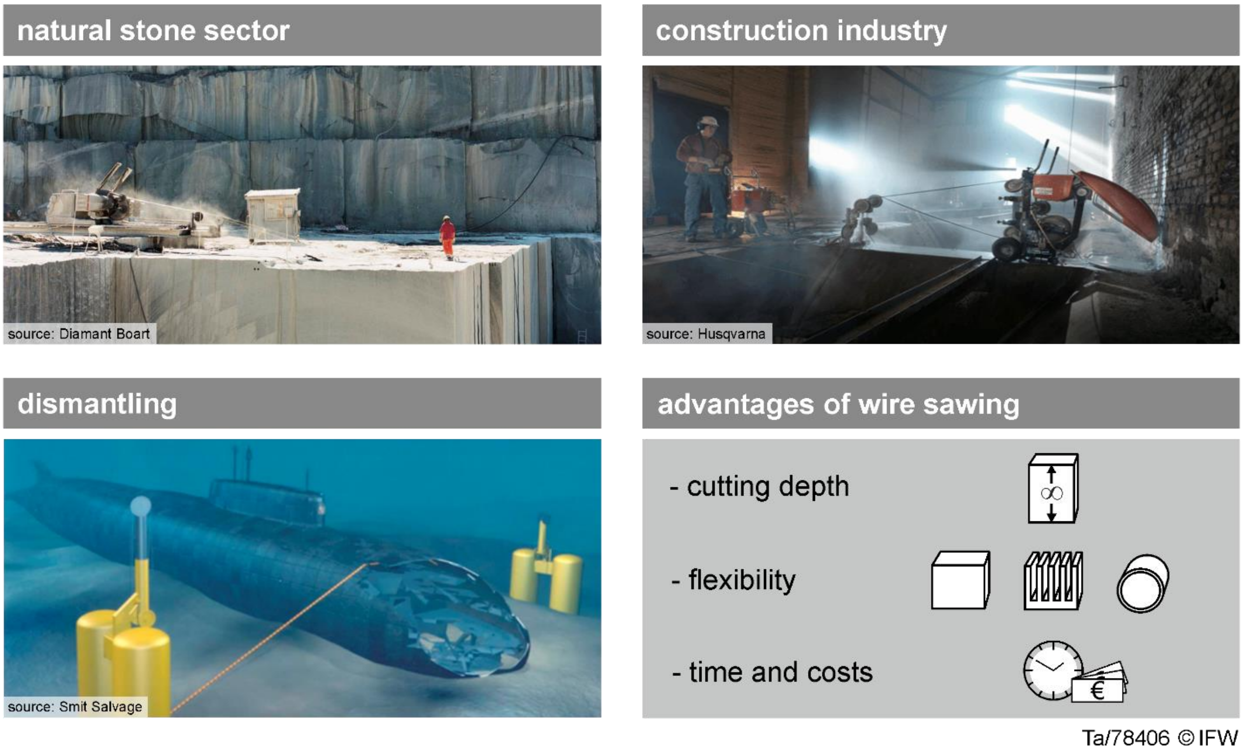

Fig. 1: Fields of application and advantages of wire sawing

1. WIRE SAWING OF STEEL

Wire sawing of steel is generally applicable [2,4,9]. Nevertheless, the achievable surface removal rate is significantly lower compared to the processing of natural stone or concrete (Fig. 2).

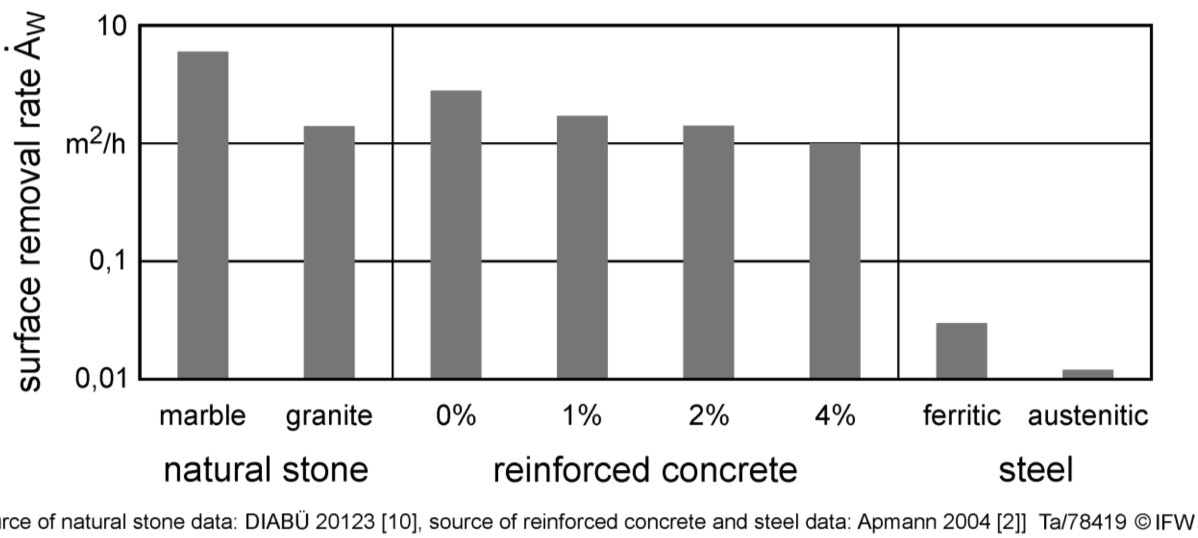

Fig. 2: Surface removal rates for natural stone, reinforced concrete with % reinforcement and steel

The reason for the lower surface removal rates is seen in the ductile cutting mechanism of steel. Furthermore, this leads to higher resulting process forces. In addition, the tool life in terms of the cut surface per metre tool is significantly lower when cutting-off metal [2]. Cut-off experiments showed that the surface removal rate can be increased by higher infeeds while the cutting speed has no significant effect on the surface removal rate [2,11]. The influence of the diamond wire pretension pressure on the material removal rate of steel with path-driven infeed has not been investigated thus far.

2. EXPERIMENTAL SETUP

In order to investigate the influence of the wire pretension on the process behaviour, cutting experiments were conducted. The experiments were performed on a wire saw with high stiffness and a high-performance electrical drive (P_N = 30 kW) (Fig. 3).

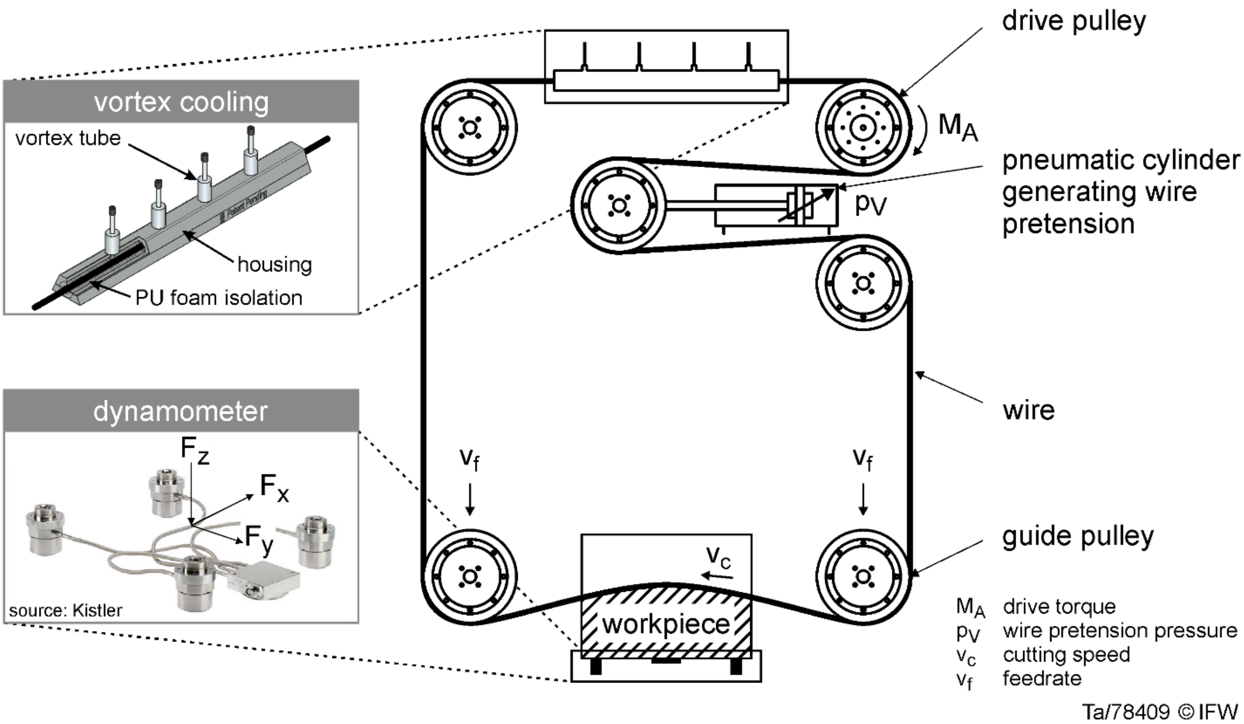

Fig. 3: Experimental setup

When dismantling a nuclear power plant cross-contamination by secondary cutting products has to be avoided. As a result, a wire sawing process without cooling lubricant is required. Therefore, during these experiments a non-liquid compressed air cooling with vortex tubes by Husqvarna was deployed matching this requirement. Four vortex tubes are positioned equidistantly on a cooling channel and generate a temperature of -14 °C inside the cooling channel. The wire saw operates in a plunging mode. The infeed is realized path-driven. A pneumatic cylinder generates the wire pretension resulting in pretension forces F_V and wire pretensions σ_V. The pretension forces were measured as a function of the wire pretension pressure with hanging scale Kern HCB 200K500. The results are depicted in Fig. 4. Process forces were measured beneath the workpiece with a 3-component dynamometer of type 9366CC by Kistler. The resulting effective power was tapped at the inverter of the drive engine. After the experiments, the height of the machined surface was measured with a digital calliper at three characteristic positions. Based on these measurements, the machined surface A_W was approximated by means of a circular segment. The surface removal rate was calculated as quotient of the machined surface A_W and the cutting time t_c.

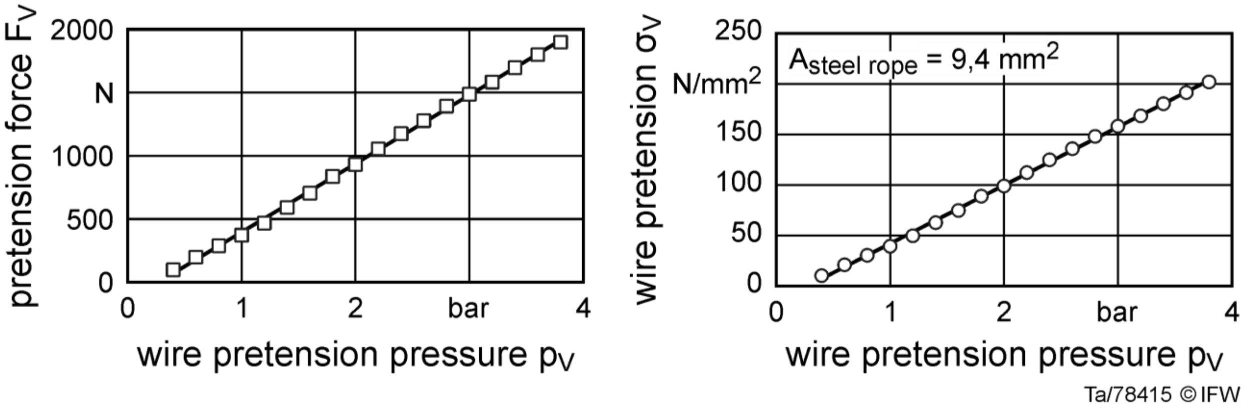

Fig. 4: Resulting pretension force and wire pretension

A solid workpiece with a cutting length of l_W = 250 mm of construction steel S355JR was cut with a diamond wire of type C1000 by Husqvarna (Fig. 5). As stated by the manufacturer, this tool is qualified for cutting steel. Diamonds are brazed in a single layer on grinding segments that are mounted on a steel rope of type 7 x 19. The diameter of the grinding segments is 10.3 mm. The spaces between the 44 grinding segments per metre are reinforced with springs and injected with synthetic rubber. The ends of the wire are linked by a connector.

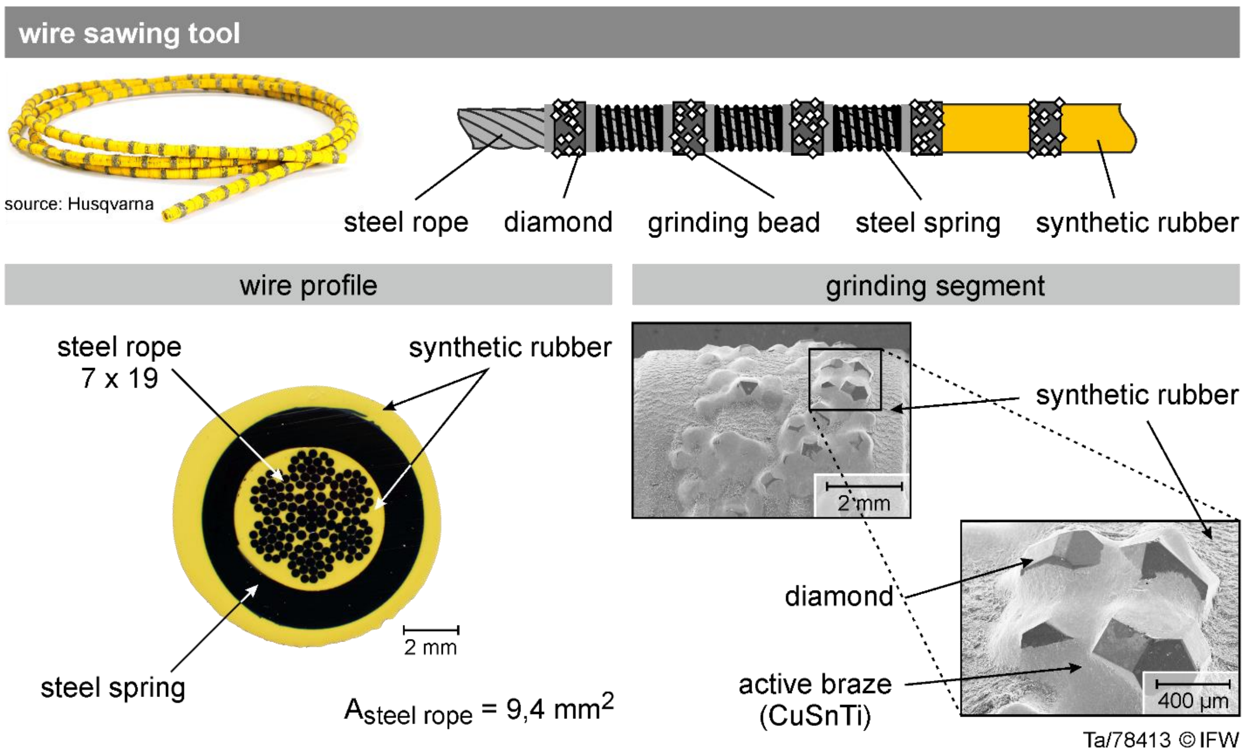

Fig. 5: Tool specifications

3. Process behaviour as a function of wire pretension

In order to evaluate the process behaviour of wire sawing tools as a function of the wire pretension pressure when cutting steel, grinding experiments were conducted. During experiments, the cutting speed v_c = 23.7 m/s, the feedrate of the guide pulleys v_f = 10 mm/min, the tool and the workpiece were kept constant. The wire pretension pressure p_V was varied in a range of 1 to 4 bar. A lower pretension pressure results in an insufficient grinding process because the idling power used to generate the cutting speed exceeds the cutting power. In preliminary tests, the connector was torn out repeatedly at pretension pressures higher than 4 bar. Therefore, this value marks the upper limit of the wire pretension pressure range. In order to reduce the influence of external variables the experiments were performed in random order.

The influence of the wire pretension pressure p_V on the surface removal rate $\dot{A}_W$ is illustrated in Fig. 6. The surface removal rate increases degressively with higher wire pretension pressures p_V. This relation can be approximated by a quadratic polynomial in a sufficient way (coefficient of determination R^2 = 95.43 %). Compared to a wire pretension pressure of p_V = 1 bar the surface removal rate $\dot{A}_W$ is increased by 120 % at p_V = 4 bar. When the applied wire pretension pressure is higher, the bending stiffness of the wire is increased. Ceteris paribus, this effect leads to a reduction of the wire deflection height h_W as seen in Fig. 6 in the right diagram. Alternatively, the deflection can be expressed in terms of the deflection radius r_W (Fig. 6). A higher deflection radius r_W is equivalent to a lower deflection h_W. Both values depend on the wire pretension pressure in a linear manner (both R^2 = 94 %).

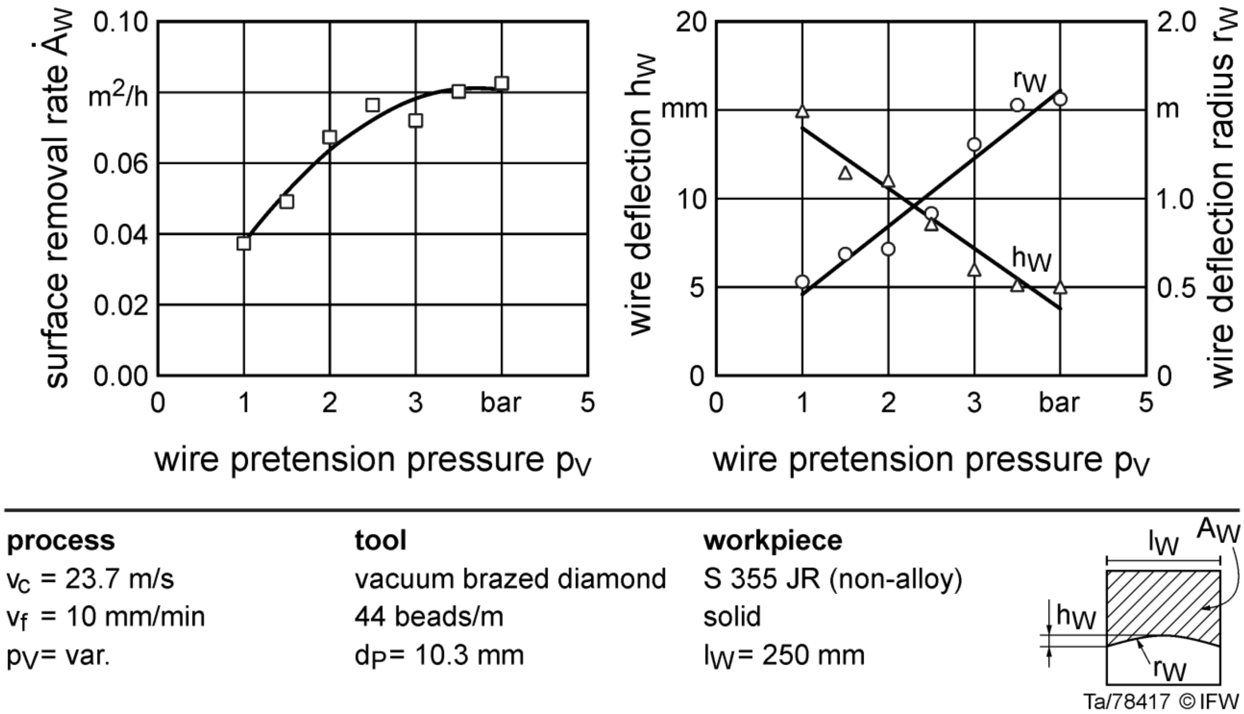

Fig. 6: Surface removal rate, wire deflection and deflection radius as a function of the wire pretension pressure

The higher bending stiffness due to the increased wire pretension pressures should result in a higher contact pressure on the workpiece as well. This assumption can be approved considering the resulting normal forces F_n. In addition, process forces are used to determine the in-process mechanical load during grinding. In Fig. 7, normal forces F_n and tangential forces F_t are depicted versus the wire pretension pressure p_V. In cutting times t_c between 800 s and 1000 s the average process forces were evaluated. Like the surface removal rate, the normal as well as the tangential forces increase with the wire pretension pressure degressively. The grinding force ratio $\mu = F_t/F_n$ is independent of the wire pretension pressure. Values of $\mu \approx 0.6$ generated in these experiments represent an effective cutting process [12].

The effective power consumption P required for a specific cutting operation is important for the machine design and the effectiveness of the process. Particularly in the context of mobile machines, this factor cannot be ignored. The effective power is the sum of the cutting power P_c, the infeed power P_f and the idling Power P_l [12]:

$$P = P_c + P_f + P_l \tag{1}$$

In comparison to the cutting speed v_c the feedrate v_f is negligibly small (here: $v_f/v_c = 7 \cdot 10^{-6}$) permitting the following simplification for the cutting power P_c:

$$v_f \ll v_c \rightarrow P_c \approx P - P_l \tag{2}$$

During grinding experiments, the effective power P and the idling power P_l were measured. In Fig. 7, both values are depicted in combination with the calculated cutting power P_c according to Equation (2). The idling power P_l slightly increases with higher wire pretension pressures due to increased friction at the pulleys. The progression of the effective power P and cutting power P_c equal the dependency of normal and tangential forces qualitatively. Furthermore, the cutting power can be calculated as product of cutting speed and the force component in the same direction [12]:

$$P_c = F_t \cdot v_c \tag{3}$$

The values calculated as difference between effective power and idling power (Eq. (2)) correlate with the cutting power calculated according to Eq. (3) in a nearly perfect positive way (Pearson product-moment correlation coefficient of r = 99,96 %).

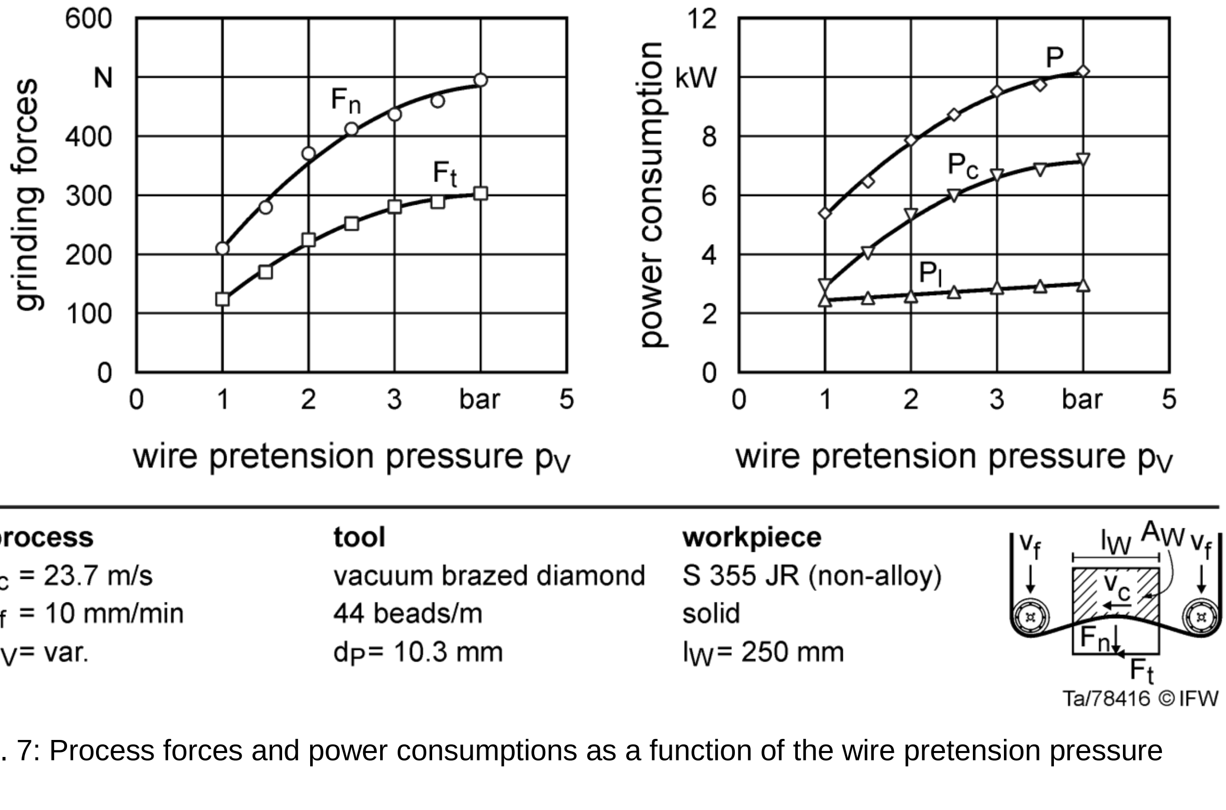

Fig. 7: Process forces and power consumptions as a function of the wire pretension pressure

The degressive behaviour of the surface removal rate $\dot{A}_W$ and the process forces F_n and F_t as a function of the wire pretension pressure p_V suggests that some kind of saturation occurs retaining all other parameters constant. The explanation is assumed as follows: At higher pretension pressures, the contact pressure is increased as well due to the higher bending stiffness. As a result, the plunge of the single grains is enhanced. By this, every grain cuts-off more workpiece material. Therefore, the surface removal rate $\dot{A}_W$ is increased. This inclination should have a theoretical maximum. After the contact pressure exceeds a specific value, the flexible wire is forced back and the surface removal cannot be increased any further.

CONCLUSION AND OUTLOOK

In this paper, the influence of the wire pretension pressure on the surface removal rate, the process forces and power was presented. Grinding experiments show that the variation of the wire pretension pressure has the potential to increase the cut-off performance of steel significantly. With a higher pretension pressure, the bending stiffness of the flexible wire is increased. As a result, a deeper penetration of the grains is achieved leading to higher single grain chip thicknesses. An increase of up to 120 % of the surface removal is measured. Nevertheless, the mechanical load on the tool and the required power are increased as well in the range of 135 % and 90 %, respectively. The relation between the wire pretension pressure and the surface removal rate, process forces as well as cutting power can be described by a degressive polynomial function in each case.

In further experiments, the tool wear will be investigated as a function of the wire pretension pressure. Furthermore, the interactions between the wire pretension pressure, cutting velocity and feed rate will be analysed. In addition, the process behaviour of wire sawing tools when cutting non-solid steel structures will be evaluated.

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