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Effects of magnetic field distributions on wire sawing performance

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ABSTRACT

To transport more abrasive grains into the cutting zone, the method of magnetic-induction free-abrasive wire sawing is proposed. A uniform magnetic field is used to magnetize a steel wire and forms a high gradient magnetic field around the wire. The magnetic abrasive grains are adsorbed on the magnetized wire and are transported into the cutting zone, which improves the wire sawing performance. The adsorption of the magnetic abrasive grains is observed using an experimental setup along the wire cross-sectional direction. The results suggest that magnetic abrasive grains are increasingly adsorbed in the paramagnetic region of the wire with increasing magnetic field intensity. Single-wire sawing experiments are conducted on a WXD170 reciprocating wire sawing machine at variable magnetic field intensity and distribution. The results suggest that the change in magnetic field intensity strongly affects the cutting efficiency, kerf loss, and surface roughness. The performance of the magnetic-induction free-abrasive wire sawing under different magnetic field intensities and distributions are compared. The wire sawing performance improves when the uniform magnetic field is evenly distributed in the cutting zone and at the top of cutting zone.

1. Introduction

Wire sawing is the most widely used technology in the photovoltaic industry. To date, the cost of wire sawing is high and accounts for approximately 20% of the manufacturing cost of solar cells [1,2]. Free-abrasive wire sawing is the main process for slicing the silicon ingots into wafers. This slicing method removes material by using a moving wire that carries the cutting fluid mixed with abrasive grains, known as slurry, into the cutting zone. The cutting efficiency of this approach is low due to the small amount of slurry that enters the cutting zone, which also contaminates and wastes silicon [3]. To improve the wire sawing process, many researchers have investigated this issue in recent years.

Ishikawa et al. [4] have studied the slurry of wire sawing by high-speed photography. The results suggest that free-abrasive wire saw slicing of horizontal films is better than no-film slicing. This is because a large amount of slurry is carried into the sawing channel by the horizontal films, which improves the cutting efficiency and surface quality. Liedke et al. [5] set up an analytical model of the macroscopic mechanical conditions in wire sawing. The model includes parameters such as wire velocity, feed velocity, tension force, and the geometry of a single-wire saw. The results were exemplified for the production line of 156 mm solar wafers, and it was found that the reduction in the viscosity of the slurry reduces the process forces and energy costs. Schwinde et al. [6] investigated the behavior of the wire during multiwire sawing in commercial large-scale production. The results suggested that material removal mainly occurred at one side of the wire. To reduce the kerf loss and wire consumption, a noncircular wire was proposed and cost-effectiveness was achieved. Li et al. [7] proposed the constant wire wear loss model to describe multiwire sawing. The model showed the relation between wire feedback ratio and process parameters based on the hypothesis that the wire wear loss is proportional to the cutting area. This hypothesis was verified experimentally. The subsequent optimized method reduced the wire cost and provided references for slicing other brittle materials by multiwire sawing. Peng et al. [8,9] proposed semifixed wire sawing with special surface microgroove structures on the wire that moved the abrasive grains into the semicontact state. This improved the cutting efficiency, surface quality, and reduced the kerf loss. However, the diameter of the semifixed wire was larger than 0.4 mm, which limited the application of the semifixed wire sawing in the production of thin wafer cells.

Nevertheless, a method for free-abrasive wire sawing that transports more magnetic abrasive grains into the sawing channel without changing the wire surface, slurry characteristic, and machining parameters should be found. Hence, a novel approach known as magnetic-induction free-abrasive wire sawing is pro-

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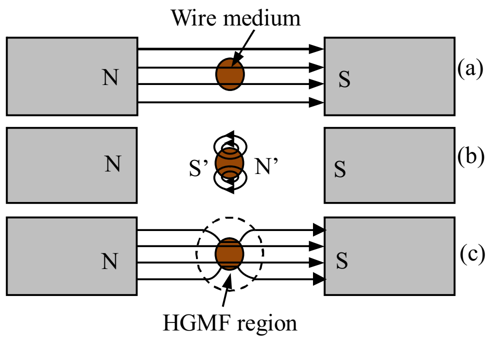

Fig. 1. Schematic of the generated high-gradient magnetic field.

posed. Magnetic abrasive grains are adsorbed in the paramagnetic region of the wire surface by magnetic forces and are moved into the cutting zone. The adsorption of magnetic abrasive grains is observed along the wire diameter direction. Single-wire sawing experiments were executed on a WXD170 reciprocating cutting machine using optical glass K9 to study the effect of magnetic field intensity and distribution on the wire sawing performance.

2. Magnetic-induction free-abrasive wire sawing

Based on the magnetic separation technology, a uniform magnetic field can be used to magnetize a ferromagnetic wire. Then, a high gradient magnetic field (HGMF) is produced around the wire (Fig. 1). The magnetic force lines uniformly extend from the N to the S pole, as shown in Fig. 1(a). When a ferromagnetic cylindrical wire is placed perpendicularly to the direction of the uniform magnetic field, the wire is magnetized and generates a new magnetic field (Fig. 1(b)). Clearly, the single wire has a reluctance effect on the uniform magnetic force lines, causing them to shrink near the single wire. The superposition of the applied and induced magnetic fields generates a local HGMF around the single wire, as shown in Fig. 1(c).

In the proposed method, known as magnetic-induction free-abrasive wire sawing, a uniform magnetic field is introduced into the traditional free-abrasive wire sawing process. Fig. 2 shows a schematic of the magnetic-induction free-abrasive wire sawing in planar and cross-sectional view. Based on the generating mechanism of HGMF, we symmetrically positioned two rectangular neodymium iron boron (NdFeB) permanent magnets, thus forming an approximately uniform magnetic field H at either side of the steel wire. The magnetic abrasive grains are affected by the magnetic force in the HGMF region. The magnetic force field around the steel wire is divided into paramagnetic (PM) and diamagnetic (DM) regions, as shown in Fig. 2(b). The paramagnetic region (A) attracts the paramagnetic abrasive grains and repels the diamagnetic abrasive grains. In the diamagnetic region (B), the conditions are the opposite. In this work, we use paramagnetic abrasive nickel-plated silicon carbide grains. Thus, they are attracted in the PM region and repulsed in the DM region [10]. During the magnetic-induction free-abrasive wire sawing process, the magnetic abrasive grains are adsorbed in the PM region (A) of the wire surface by the attractive forces and then are transported into the cutting zone by the steel wire with velocity V. Hence, the number of magnetic abrasive grains into the cutting zone increases, thus improving the cutting efficiency. The magnetic abrasive grains are repulsed in the DM region (B) of the wire surface, which reduces the number of large abrasive grains directly in contact with the wire and kerf side, thus leading to kerf loss and surface roughness reduction.

Table 1
Observation parameters.

Parameter	Value
Wire diameter (d)	0.4 mm
Mean diameter of magnetic abrasive grains (b)	25 μm
Cutting fluid viscosity (η)	0.04 Pa s
Initial slurry velocity (V_0)	3 mm/s

3. Direct observation of the adsorption of magnetic abrasive grains

3.1. Experimental conditions

Due to the difficulty of observing the adsorption of magnetic abrasive grains in practice, we constructed an experimental setup to model the wire sawing process along the wire diameter direction, as shown in Fig. 3. Thus, we investigated the adsorption of the magnetic abrasive grains and verified the effect of the magnetic field in the free-abrasive wire sawing process. We used a high-speed camera, manufactured by the Keyence Corporation, and an optical microscope with 200× magnification. The microscope lens was placed directly above the wire. The uniform magnetic field was constructed using two rectangular $40 \times 20 \times 10\,mm^3$ NdFeB permanent magnets that attract each other. A copper-coated steel wire with diameter of 0.4 mm is placed between the two magnets and is fixed using a device manufactured by 3D printing. The slurry used comprises magnetic abrasive grains and polyethylene glycol (PEG)300 as carrier. To allow for good observation, the concentration of magnetic abrasive grains was 1%. Magnetic field intensity of 0, 3.18×10^4, 6.36×10^4, and 9.54×10^4 A/m were selected to investigate the effect of the magnetic field intensity (H) on the distribution of the magnetic abrasive grains. The magnetic field intensity was varied by adjusting the distance between the two magnets and was measured by a Gaussmeter at the wire position. The slurry (20 ml) was separately supplied into the device through the slurry entrance at different magnetic field intensities and its flow volume was controlled by a liquid flow meter. Then, the adsorption of the magnetic abrasive grains was recorded by the high-speed camera. The experimental parameters are listed in Table 1.

3.2. Results

Fig. 4 shows the experimental results for the adsorption of the magnetic abrasive grains along the wire diameter direction. Few abrasive grains are suspended on the wire surface, as shown in Fig. 4(a), which may relate to the high viscosity of the fluid. It indicates that the number of abrasive grains carried into the cutting zone is small in the conventional free-abrasive wire sawing process. Clearly, many magnetic abrasive grains are adsorbed on the wire surface in the magnetic-induction free-abrasive wire sawing process, and an increasing number of magnetic abrasive grains is adsorbed on the wire with increasing magnetic field intensity, as shown in Fig. 4(b)–(d). The distribution of magnetic abrasive grains is asymmetrical. More specifically, the upstream grain buildup is larger than the downstream case, which may be related to the perturbation of the particle motion. This result is consistent with the report of Birss et al. [11]. Hence, the increasing magnetic field intensity (H) helps to transport more magnetic abrasive grains into the cutting zone by the wire. In addition, the observations suggest that the magnetized wire can achieve free-abrasive wire sawing in a uniform magnetic field.