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Study on the formation mechanism of the magnetic abrasive particle layer on the surface of saw wire in magnetic induction-free abrasive wire sawing

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ABSTRACT

Magnetic induction-free abrasive wire sawing is a hybrid process that introduces the high gradient magnetic field into traditional free abrasive wire sawing technology. A ferromagnetic saw wire is magnetized by the external uniform magnetic field, and it then generates a high gradient magnetic field around itself. Magnetic abrasive particles are attracted to the surface of the wire by the magnetic force, which leads to more abrasive particles in the sawing channel. This novel method effectively improves the utilizing rate of abrasive particles and is helpful to improve the wire sawing performance. In this study, the formation mechanism of the magnetic abrasive particle layer on the surface of saw wire is investigated theoretically and experimentally. Based on force analysis of the magnetic abrasive particle on the wire surface, a mathematical model for analyzing the formation mechanism of the magnetic abrasive particle layer is presented and studied by the numerical analysis software MATLAB. An experimental platform utilizing a high-speed camera is constructed to observe the formation of the magnetic abrasive particle layer on the wire. The experimental results reveal that the magnetized wire can adsorb lots of magnetic abrasive particles, thus leading to the formation of a magnetic abrasive particle layer. The shape of the magnetic abrasive particle layer approximates to an annular sector. Moreover, the thickness of the magnetic abrasive particle layer increases as the external uniform magnetic field strength increases. The experimental results verify the theoretical results. The present model is applied to study the formation mechanism of the magnetic abrasive particle layer on the surface of saw wire in magnetic induction-free abrasive wire sawing in detail.

1. Introduction

Silicon wafers are the substrate materials of solar cells. Slicing is a key process in the fabrication of silicon wafers. Its cost accounts for about 20% of the manufacturing costs of solar cells [1]. Wire sawing technology is the most widely used for wafer preparation. It includes free and fixed abrasive wire sawing approaches. The diamond wires used in the fixed abrasive wire sawing process are more expensive than the steel wire used in free abrasive wire sawing process. Moreover, this type of wire removes materials mainly through a “scratch” process, leading to great damage on the silicon wafers [2]. These disadvantages limit its application in the photovoltaic (PV) industry. Free abrasive wire sawing is a current leading technology for slicing silicon ingots into wafers because of its small kerf loss, good surface quality, and the ability to cut ingots of large size [3]. Cutting is achieved by a moving wire that transports the slurry consisting of the slurry carrier, typically oil or polyethylene glycol (PEG) based, and SiC abrasives into the sawing channel. However, it has disadvantages of low cutting efficiency, saw wire damage and serious contamination of the environment [4]. To improve the free abrasive wiresaw slicing process, researchers have carried out broad investigations.

In order to understand the material removal mechanism of free abrasive wire sawing completely, Kao et al. investigated the effect of multiple simultaneous indentations on the material's response using the finite element method. The results showed that the load required to achieve a prescribed depth for silicon decreases as the spacing between the abrasive particles decreases. Namely, the indentation peak depth increases at a prescribed load as the spacing between the abrasive particles decreases. Hence, the material removal rate increases at a given load as the spacing between the abrasives decreases [5]. Nassauer et al. studied the mechanism of wire sawing at the micro level both by numerical simulation and experiments. The results showed that the number of involved particles was very low. Wire sawing technology removed materials mainly by large particles clamped between wire and ingot. It could still remove materials when the distance between wire and ingot was larger than the particle diameter. This was the case when two particles were rolling over each other and interacting with wire and ingot [6]. Anspach et al. used structured wire whose longitudinal axis is a non-straight line to perform the single wire sawing

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experiments. The experimental results showed that 45% less wire consumption and 40% less slurry consumption of structured wire were achieved in comparison with straight wire. In addition, the structured wire transported the slurry grits more uniformly into the sawing channel than the straight wire. However, the drawbacks of structured wire were the larger kerf loss and high probability of wire breakage [7]. Wang et al. proposed a new technique called abrasive electrochemical multi-wire slicing (AEMS), which combines the functions of electrochemical reaction and mechanical grinding. In this approach, material removal was achieved by the interaction of grinding and anodic oxidation, which significantly improved the surface integrity and slicing efficiency [8–9].

Our proposed method, referred to as magnetic induction-free abrasive wire sawing (MIFAWS), applies the external uniform magnetic field around the ferromagnetic wire during wire sawing. In this hybrid process, the slurry is made of PEG300 and magnetic abrasive particles (Nickel plated SiC). A large number of magnetic abrasive particles are collected on the wire surface by the magnetic force of magnetized wire. It attracted more abrasive particles into the sawing channel between wire and the work-piece and improves the wire sawing performance. This novel method is similar to the Magnetic Abrasive Finishing technology, wherein magnetic abrasives are accumulated by magnetic force and form a flexible magnetic abrasive brush. The abrasive particles in the brush interact with the workpiece surface to remove materials [10]. A further study on the formation mechanism of the magnetic abrasive particle layer in MIFAWS process should be conducted. Previous modeling studies [11–12] ignored the magnetic force field partitions around the wire, which have significant influence on the adsorption behavior of magnetic abrasive particle, thus affecting the particle layer formed on the wire surface. In addition, previous modeling studies [11–12,19] lack a detailed experimental verification. Besides, there is little literature [13] studying the magnetic abrasive particle layer formed on the wire surface in the MIFAWS process and the mechanism of the effect of magnetic field intensity on the magnetic abrasive particle layer is still not investigated. In this paper, to further elucidate the mechanism of this novel approach, we analyze the force acting on the magnetic abrasive particle on the wire in a mathematical model considering the influence of magnetic force field partitions and follow the formation of the magnetic abrasive particle layer in numerical computation. The results are verified in experimental observations of the formation of the magnetic abrasive particle layer on a platform utilizing a high-speed camera.

2. Principle of MIFAWS

Stainless steel wire, commonly used in free abrasive wire sawing, is a kind of ferromagnetic material. It is magnetized and then generates a high gradient magnetic field around itself when put in an external uniform magnetic field. In this way, we put forward magnetic induction-free abrasive wire sawing (MIFAWS). The high-gradient magnetic field (HGMF) around the single wire is schematized in Fig. 1.

Based on the mechanism of how an HGMF forms (shown in Fig. 1), the MIFAWS technology applies a uniform magnetic field to the traditional free-abrasive wire sawing process. During the MIFAWS process, we symmetrically positioned two permanent magnets at either side of the steel wire to approximately produce the background uniform magnetic field. The magnetic field is uniformly distributed near the entry to the sawing channel (Section I) and in the sawing channel (Section II), and its direction is parallel to the slurry and work-piece feed directions, as demonstrated in Fig. 2(a). A high-gradient magnetic field is produced around the magnetized wire. Moreover, the magnetic force field region around the wire is divided into paramagnetic (PM) and diamagnetic (DM) regions, as shown in Fig. 2(b). The PM region (A) attracts PM abrasive particles, while the DM region (B) repels PM abrasive particles. The abrasive particles in the MIFAWS technology are fabricated from nickel-plated SiC, which is paramagnetic. Hence, the wire PM region adsorbs many nickel-plated SiC abrasive particles by the magnetic

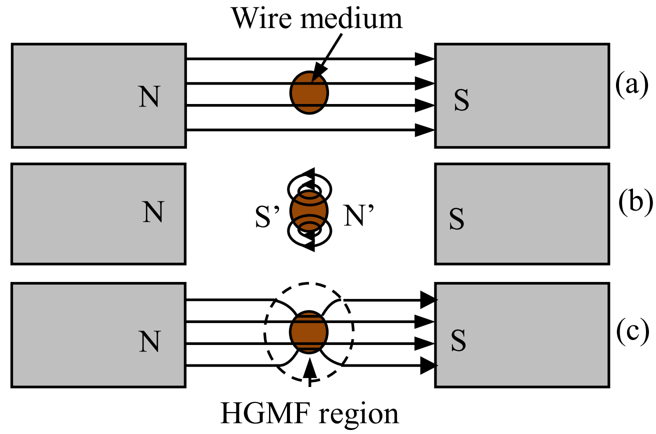

Fig. 1. Schematic diagram of how an HGMF is generated. (a) The magnetic force lines uniformly extend from the N to the S pole. (b) Wire medium is magnetized and produces a new magnetic field. (c) The superposition of the external and induced magnetic fields produces a local HGMF around the wire medium.

force, thus leading to more magnetic abrasive particles being transported from Section I to Section II. This novel method effectively improves the utilizing rate of slurry and is helpful to improve the wire sawing performance; for example, a higher material removal rate and smaller kerf loss were achieved. This has been validated in our previous study [14].

3. Theoretical analysis of the formation of the magnetic abrasive particle layer

Magnetic abrasive particles are mainly affected by magnetic force and fluid drag force when in motion with the fluid around the ferromagnetic wire. Some magnetic abrasive particles are adsorbed on the wire surface or other magnetic abrasive particles that have been adsorbed on the wire surface. We assume that magnetic abrasive particles on the saw wire surface are stationary or, at least, instantaneously stationary. So, the magnetic abrasive particle is detained on the wire surface if the net force is pointing to the region where the attraction is relatively large. Otherwise, the magnetic abrasive particle will move toward the region where the attraction is small and finally away from the wire surface [15]. Assuming that the magnetic abrasive particles are closely packed and adsorbed on the wire layer-by-layer until forming an unstable layer, we define this process as the formation of the magnetic abrasive particle layer on the wire surface.

The magnetic particle shape is spherical and the wire is an infinitely long cylinder for simplified analysis. Moreover, we do not consider the interaction between magnetic abrasive particles and only consider the magnetic abrasive particle layer formed on the wire side toward the direction of fluid motion. Fig. 3 shows a schematic of the force analysis of a magnetic abrasive particle on the wire surface.

Magnetic force $\boldsymbol{F}_{\mathrm{m}}$, a key force in adsorbing the magnetic abrasive particle on the wire surface, can be expressed as [16–17]

$$\boldsymbol{F_m} = \frac{1}{2}\mu_0 K V \nabla\left(\boldsymbol{H}^2\right) \tag{1}$$

Here, μ_0 is the vacuum permeability ($4\pi \times 10^{-7}$ H/m). K is the magnetic susceptibility difference between the magnetic abrasive particle and fluid. Usually, the magnetic susceptibility of the fluid is far less than that of the magnetic abrasive particle, so K approximates the magnetic susceptibility of the magnetic abrasive particle. $\boldsymbol{H}$ is the magnetic field strength of the location $P(r, \theta)$. V represents the volume of the magnetic abrasive particle, which is formulated as $V = 4\pi b^3/3$; here, b is the radius of the magnetic abrasive particle.