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Inline diamond wire inspection based on resonant vibrations

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ABSTRACT

Because the wire itself is the dominant cost in diamond wire sawing, economics dictate that the wire life must be prolonged. This paper presents recent progress made in real-time non-contact monitoring of diamond wire using the resonant vibration (RV) characteristics of the wire. This technology was successfully demonstrated on a diamond wire manufacturing line moving at 0.25m/s and showed excellent sensitivity to both plating metal thickness and diamond particle density, despite minor fluctuations in the tension. Additionally, a theoretical framework is presented which shows that the characteristics of the resonance curve do not change at speeds above 500m/s. As a result, this technology is expected to be able to meet the increasing demands of monitoring diamond wire wear during sawing as the wire speed continues to increase in the coming years.

Introduction

As well as factors such as wire construction, wire management [1], sawing conditions, coolant properties, and material hardness, inline sawing metrology is expected to play a significant role in extending the life of the wire [2]. The need for an effective metrology to monitor diamond wire arises from the high cost of raw materials, and therefore the necessity to avoid waste. For diamond wire manufacturers, the cost/km of raw materials (core wire, diamonds, and plating metal) is the most significant.

> "The need for an effective metrology to monitor diamond wire arises from the high cost of raw materials."

If it is assumed that only a fraction of a 250km spool is plated out of specifications, the result could be a loss in the thousands of dollars. In the worst-case scenario, the entire spool would have to be discarded, since the metal and diamond cannot be recovered in a cost-effective way. Similarly, losses for wafer manufacturers can be significant in the event of diamond wire failure during sawing due to wire wear or a structural defect; losses would include scrapped silicon, scrapped wire, and tool downtime to clean up the saw and rewire the web.

To mitigate these challenges, there are optical techniques available for inspecting the diamond wire plating process inline [3,4]. However, these techniques suffer from several limitations:

- The wire is not continuously inspected from start to finish, but rather spot checked at regular intervals.
- The imaged wire profile is used to compute the plating thickness and diamond concentration, even though a large area fraction of the wire remains invisible.
- Since optical approaches provide only surface diagnostics, it is not possible to detect potential subsurface defects, such as a defective core or plating-metal delamination.
- Because of the sheer amount of data required in image processing, an inline inspection in the case of high-speed applications (i.e. diamond wire sawing) is a serious challenge.
- The ingot cutting process creates a considerable amount of residue; this is harmful for high-resolution optics hardware, potentially requiring substantial tool downtime for cleaning and maintenance.

Clearly, an effective diamond wire metrology needs to successfully address all these challenges.

Inline RV metrology on the diamond wire manufacturing line

A novel inline resonant vibration (RV) sensor developed through a c-Si PVMC collaborative programme was installed at the end of a diamond wire manufacturing line, with only minor modification. An additional pulley was introduced before the take-up spool set-up because of the wire moving up and down during spooling and thus causing a lateral force on the pulley adjacent to the sensor. In order to benchmark this new technology with existing optical metrology, computer clocks, sensor position and line speed were used to synchronize the optical and acoustic measurements. The optical data covers approximately 3mm of wire length, taken every 300mm, resulting in 1% of the wire being inspected. On the other hand, the RV data is taken continuously along the entire length of the wire. The core diameter used for this experiment was 250µm.

Fig. 1 shows the normalized peak frequency from RV metrology superimposed on a graph of the plated metal thickness generated from the optical metrology. The RV peak indicates an inverse correlation with the plated metal thickness, despite an estimated 10% variation in the tension on the basis of pre-run data. Nonetheless, the sensitivity to metal thickness is quite pronounced, as seen in Fig. 2.

Next, Fig. 3 shows the normalized

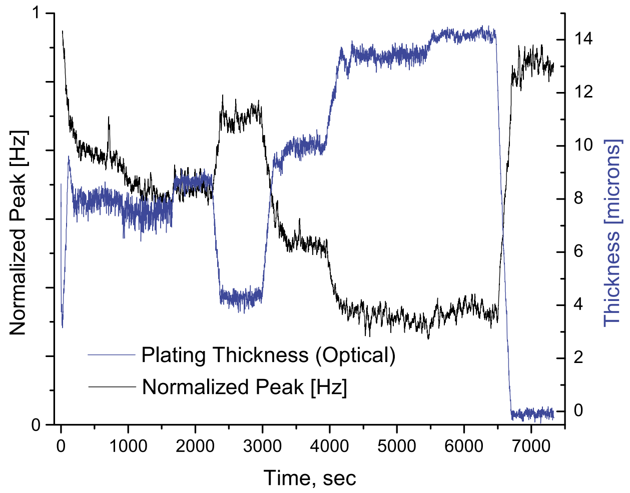

Figure 1. Normalized peak frequency (RV metrology) and plated metal thickness data (optical metrology).

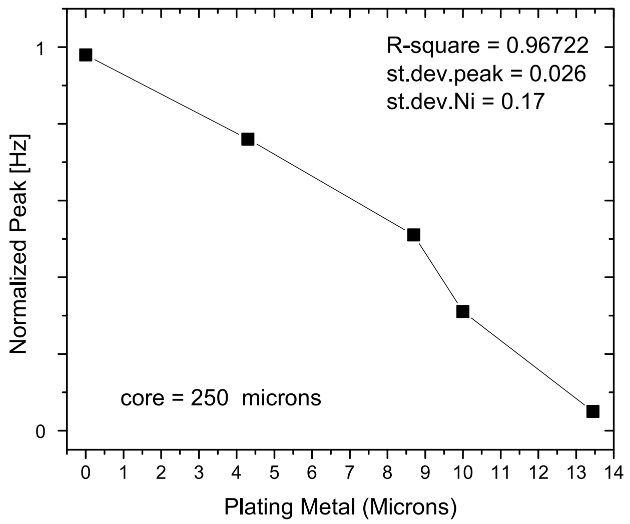

Figure 2. Normalized peak frequency (RV metrology) vs. plated metal thickness data (optical metrology).

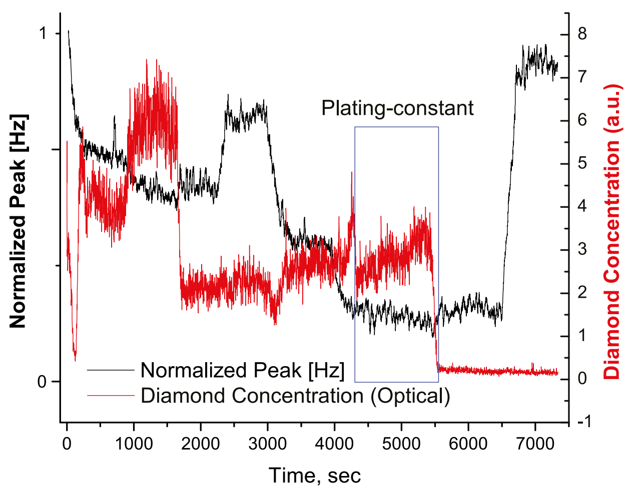

Figure 3. Normalized peak frequency vs. diamond wire concentration.

peak frequency from RV metrology vs. the diamond concentration data generated from the optical metrology. From 4,500 sec to 5,500 sec (the time window indicated by a blue rectangle), the rate of plating was kept constant, while the diamond concentration was increased. Within that time window, the decrease in the peak frequency (black curve) is the result of an increase in diamond concentration (red curve). Here again, there is an inverse correlation between the peak frequency and the diamond particle concentration. Outside the identified time window, there is no clear correlation between peak frequency and diamond particle concentration, because the plating rate was allowed to change, thus affecting the peak frequency. In order to clearly see the correlation with diamond particle concentration, the effect of the plating would have to be decoupled. Furthermore, the noise in the measured RV peak frequency is much less than in the optical data, even with fluctuations in the tension.

It is expected that the noise in the data can be minimized by correcting the RV sensor data using the real-time measurements of the wire tension. This will be the focus of future work.

Theoretical framework for high-speed monitoring

The theoretical framework of resonance vibrations of a stationary wire has been developed and subsequently extended to a moving wire [5,6]. Analytical equations were formulated and solved, and oscillation damping was analysed in Voigt and Maxwell models. Because the wire core diameter is expected to continue decreasing to 70µm within the next two years, the numerical calculations presented below were performed for a core diameter of 70µm and a tension of 10N. The first and most significant result is that resonance frequency is independent of diamond wire speed, which is shown in Fig. 4 by the curves being virtually indistinguishable. This means that this inline metrology can be used as wire speed continues to increase.

Fig. 5 shows the vibration modes of the diamond wire at speeds of up to 40m/sec. Unlike the peak frequency, the shape of the vibration modes becomes slightly distorted as the speed increases.

Finally considered is the case of a wire moving at a very high speed such that damping occurs on the time scale of the vibration. The vibration mode of the diamond wire is severely distorted,

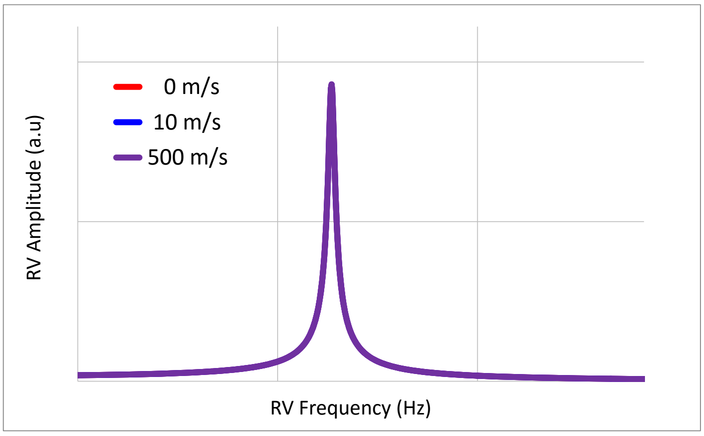

Figure 4. Resonance curve for stationary and moving diamond wire.

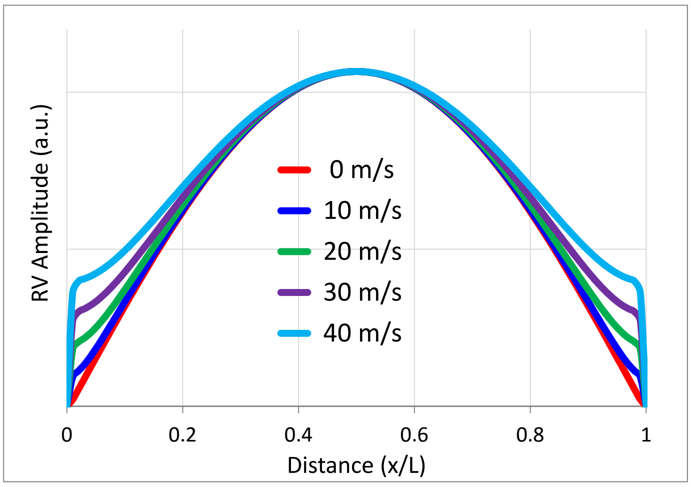

Figure 5. Vibration mode vs. diamond wire speed.

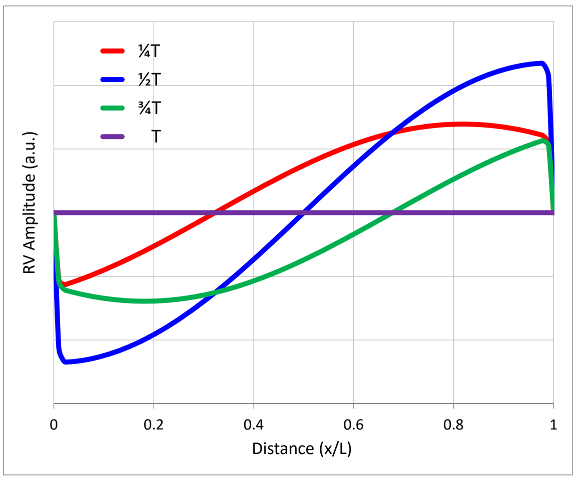

Figure 6. Vibration modes for a fast-moving diamond wire at 150m/s.

as portrayed in Fig. 6, and even though the resonance damping or bandwidth is slightly affected, the resonance frequency remains unchanged from the stationary case, as shown in Fig. 4. As a result, peak frequency is an ideal metric for diamond wire monitoring as wire speeds increase in wafer manufacturing.

> "The proposed new metrology is expected to be a sustainable solution as wire speeds increase."

Conclusion

Non-contact monitoring of diamond wire properties using the RV characteristics of the wire has been demonstrated on a diamond wire plating line with wire speeds of up to 0.25m/s. The RV peak shows a clear inverse correlation with plated metal thickness and diamond density when the plating rate is maintained at a constant value. The accuracy of this novel metrology can be further improved by incorporating real-time tension data. Moreover, the theory predicts that the RV peak is independent of the wire speed, unlike the vibration modes and to a lesser degree the damping. As a result, the proposed new metrology is expected to be a sustainable solution as wire speeds increase.

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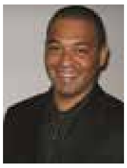
About the Authors



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