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**on the stiffness of wire web of multi-wire sawing machine and its influence on machining accuracy**

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**Abstract**

Diamond wire sawing has gradually applied as the dominant way of silicon sawing in the photovoltaic and semiconductor industry. In this paper, a model of stiffness of wire web was established, and the corresponding test measure, process, and evaluation standard were proposed. Lack of stiffness of wire web could easily cause wire bow and further reduce the machining accuracy during diamond wire sawing. And the machining accuracy due to wire bow was analyzed. The special significance of this study is considered the stiffness of wire web to be the key index of multi-wire sawing performance. Through this method, the wire bow and the lack of cutting accuracy can be reasonably evaluated. As a result, wire lag and wire bow due to the loss of the stiffness of wire web could be minimized, as well as its influence on machining accuracy. Static stiffness matrices of wire web were presented to analyze the influence of the feed position and the number of wires forming the wire web on the stiffness of wire web. Moreover, a FEM model was established to find the influence factors such as wheel span, wheel diamond, and preset tension on the stiffness of wire web.

**Keywords** Stiffness of wire web • Stiffness matrix • Sawing accuracy • Sawing stiffness • Cutting efficiency • Wire bow

**1 Introduction**

At present, the main processing methods for silicon wafer are diamond wire sawing and slurry wire sawing [1, 2]. With the development of technology, diamond wire sawing has made great progress in efficiency and quality, but the reciprocating cutting problems such as wire marks and tension fluctuation are still need to improve [3]. Generally, the way to improve the processing quality is to use finer diamond wire, improve the synchronicity of moving parts, and increase wire speed and satisfy feed speed to improve tension loss, in order to give full play to the cutting capability of diamond wire to ensure the accuracy [4, 5]. In addition, as a special machine tool, the stiffness performance of multi-wire sawing machine will also affect the processing quality.

In the design and evaluation of diamond wire sawing machine, little researches on stiffness are presented. But in the field of traditional metal cutting machine tools, stiffness is an extremely important performance index. The support stiffness of machine tool should be properly designed for reducing both the ground disturbance vibration and the drive disturbance vibration [6]. The stiffness of the motion and running parts of the machine tool are considered the key components that affect the processing efficiency and accuracy. In the research of the spindle stiffness, Sarenac [7] considered that spindle stiffness is the main contribution of the machine tool stiffness. Bearings, inter-distance relations, and console length and other constructional parameters were emphasized. Yen [8] investigated the different approaches on a servo control board and with the ability to change the servo control algorithms on a test machine tool to test the performance of servo stiffness. As for the design and modeling method of stiffness, many scholars have studied it from a long time ago, such as Schenk in 1939 [7] who proposed model of spindle as elastic beams. Kono [6]...
proposed a 3D stiffness model of a machine tool support using contact stiffness which was obtained by multiplying the unit contact stiffness by the real contact area. By using the proposed stiffness model, the natural frequency and vibration mode shape of a machine tool bed was predicted. Li [9] introduced a novel approach for designing the stiffener layout inside large machine tools by applying the self-optimal growth principle of plant ramifications in nature.

As for the measurement methods of stiffness, several researches have been presented. Majda [10] adopted a method of measuring machine tool stiffness based on the model of rigid body motion, which enabled measurements to be made in generalized coordinates, including measurements of translational and torsional stiffness. This allowed testing the stiffness of various medium-sized machine tools—lathes—and milling machines. Laspas [11] presented a novel measurement procedure to measure and identify full translational stiffness matrices of 5-axis machining centers using quasi-static circular trajectories. The research expanded the measurement procedure to a calibration procedure for 5-axis machining centers and identifies rotational stiffness. Different from the measurement method, CAE method has been used in the research of machine tool stiffness for a long time. Huang [12] introduced a single-module method and a hybrid modeling method for analyzing the stiffness of machine tools by using CAE modelling.

Similar to the traditional machine tool design, in order to improve the machining accuracy of diamond wire sawing, the stiffness design of wire web should be considered a design item. This is the main purpose of this paper. Because the movement form of DWS is simple as only one movement axis in the feed direction, its dynamic performance is less affected by the movement axis. The elastic diamond wire is different from the rigid tool of traditional machine tool, and the influence of vibration on machining is limited by the damping effect of wire. Therefore, unlike the dynamic stiffness used to evaluate the dynamic performance of equipment [13], the static stiffness is more suitable for the stiffness evaluation of wire web.

As the multi-wire sawing machine tool is composed of many parts, each part will deform under the action of load, which will lead to the relative displacement between diamond wire and silicon ingot, and the displacement is a comprehensive amount. The stiffness of a machine tool cannot be evaluated by the stiffness of a certain part but refers to the capability of the whole machine tool to resist deformation under the action of cutting force [14]. Different from traditional machine tools, multi-wire sawing machine tools use abrasive grains to slide silicon material through the relative movement of diamond wire, and the elastic deformation of diamond wire is significantly larger than other parts of the equipment [15]. In the actual machining, under the action of cutting load, the wire web will deform along the force direction to form a wire bow [16]. These deviations will bring adverse effects on the machining, such as lose of accuracy and the deterioration of surface roughness. If the stiffness of wire web can be accurately measured, it plays an important role in understanding the processing capability of diamond wire sawing machine tool, and improving the processing accuracy and efficiency.

In this paper, the static stiffness of diamond wire web was discussed. The relationship between wire deformation and loading force was found. The purpose of the research is to put forward the definition and measurement method of stiffness of wire web and take it as an important index to evaluate the performance of multi-wire sawing machine tool. Furthermore, the influence factors on the stiffness and their trends which lead to the problem of machining accuracy were discussed to establish competitiveness of diamond wire sawing machine tool.

## 2 Research method

### 2.1 Definition of stiffness of wire web

The static stiffness of diamond wire web refers to the capability of the wire web to resist the relative position change caused by the static force in the specified direction, mainly in the feeding direction of the silicon ingot relative to the wire web. It is an important factor to improve the machining accuracy and stability of multi-wire machines. The static stiffness can be calculated by the ratio between the loading force and the deformation of diamond wire caused by the external force. At present, there is no standard about the stiffness of wire web, which can be determined to meet the requirements for equipment acceptance. Each enterprise and user can formulate their own standards according to their own situation.

### 2.2 Detection and calculation method of static stiffness

The relationship between the force and wire deformation is approximately linear. The average static stiffness can be calculated by the ratio of force increment to displacement increment. The data can also be processed by the successive difference method and the least square method to obtain the static stiffness.

The static stiffness is obtained by Eq. (1). In order to reduce the measurement error, the wire deformation under the action of multiple incremental forces is usually measured continuously, and then the equation is obtained by linear fitting. The coefficient of the linear equation is the static stiffness value of the wire web:

\[ K_f = \frac{F_f}{D_f} \] (1)
where $F_f$ is the loading force applied in the feed direction and $D_f$ is the wire deformation in the feed direction caused by the load.

The stiffness measurement method of diamond wire web is shown in Fig. 1. The process is as follows: (1) The loading device moves and contacts the wire web according to the specified number of wires and then records the feed position. (2) Continue to increase the unit feed, record the corresponding force under this feed. (3) Increase the feed position in turn, and record the force under each feed increment until the wire bow of the wire web reaches a certain value and has enough strength when the measurement can be stopped after enough data.

3 Experiment

3.1 DWS equipment and measuring instruments

3.1.1 Sawing machine tool

The sawing equipment used in the experiment is a GC630S multi-wire sawing machine tool added tension adjusting function, as shown in Fig. 2. The silicon ingot is fixed on the force sensor which is set on the feed mechanism during the cutting test, while the press plate is fixed on the force sensor during the stiffness test. The size of press plate used in the test is 50 mm × 120 mm.

3.1.2 Test instrument

The loading forces are measured by force measuring system consist of ME NC-3DT60 (K3D60) three component force sensors and DASP V11 test system. The force is increased by equal spacing increment. The direction of the force action simulates the direction of multi-wire sawing, that is, the feeding direction of silicon ingot. The action point of the force is concentrated on the middle position of silicon ingot and diamond wire in each experiment. The displacement test is recorded according to the actual feed rate displayed by the control system of the multi-wire sawing machine tool.

Fig. 1  Stiffness measuring principle of multi-wire sawing web

3.2 Experimental design

3.2.1 Stiffness test of wire web

The stiffness test of wire web is designed by changing the number of diamond wires that make up the wire web. The measurement method mentioned above was repeated to measure the static stiffness. In the test, the force sensor is placed on the workpiece feeding mechanism. The feed position along the feeding direction is taken as the reference position when force signal is changed. The feed rate is used to express the displacement. After the end of the first feed position, it stays for about 10 s and gradually incrementally presses down the wire web. Continue to press the wire web incrementally to realize deformation difference of wire, measure the change of force and record the incremental displacement. After the end of force measurement at each subsequent feed position, the incremental displacement time is about 12 s, and multiple force data corresponding to different positions is measured. The displacements and forces are recorded and taken as the data of static stiffness calculation. The experiment was carried out at ambient temperature of 20 °C.

The diamond wire used in the static stiffness test is 50 wire with a diameter of 0.066 mm and a preset tension of 6.5 N in the test. The broken tension and broken stress of 50 wire are 10 N and more than 4000 MPa, respectively. (Note: The diamond wire is composed of steel wire as core wire, electroplated layer, and abrasive grains. The diameter of core wire is 50 μm which is defined as 50 wire. The overall diameter of the diamond wire is 0.066 mm.)

3.2.2 Cutting test

The wire web composed of different number of wires is used to cut different lengths to sawing kerfs. The system parameters such as feed distance are recorded (Table 1), as well as the cutting forces in the sawing process are measured by the force sensor. The stiffness of wire web during cutting could be calculated by the ratio of feed force to the theoretical sawing distance. Meanwhile, the wire bows generated during wire sawing are indirectly measured by the formed kerfs on the side of silicon ingot. As a result, the influence of wire web stiffness on sawing accuracy could be evaluated. The process used in the test is shown in the Table 2, and part of the silicon material used in this research is shown in Fig. 3. In the process of reciprocating wire sawing, unused diamond wire continuously enters the cutting zone. Therefore, in a single reciprocating cycle, the wire amount at the wire providing side is higher than the wire amount at the wire receiving side. In this test, the wire providing amount is set to be 5 m higher than the wire receiving amount.
4 Results and discussion

4.1 Static stiffness of wire web

The feed force measured in the static stiffness test is shown in Fig. 4. The feed force increases with the wire deformation increases no matter the wire number \( N = 5, 10, \ldots, 40 \). With the same increment displacement, the more wire number is, the greater the feed force will be. The relation between the feed force and wire deformation is linear. The static stiffness curve can be obtained as shown in Fig. 5. The static stiffness of wire web composed of different number of wires could be recognized by the coefficient of linear equation in the figure.

In addition, the lateral force and force in the cutting direction corresponding to the feed force also show an increasing trend. The lateral force in Fig. 6a shows a linear positive proportional relationship between the lateral force and deformation. However, the relationship between the force and wire deformation along the wire speed direction is not completely linear, as shown in Fig. 6b.

Fig. 7 shows the relationship between the stiffness of wire web and the number of wires forming the wire web. From the left coordinate axis, it can be seen that a linear relationship between the stiffness of wire web and the number of wires existed. The stiffness of wire web could be improved by increasing the number of wire that forming the wire web. From the right coordinate axis, it can be seen that the stiffness of single wire forming the wire web decreases slightly when the wire web changes from 5 wires to 40 wires. But on the whole, the stiffness of a single wire forming the wire web is basically stable between 0.0031 and 0.0034 N/mm when the wire number is 5, 10, 15, 20, 25, 30, 35, and 40. The stiffness of a single wire can be considered the unit contact stiffness, that is, the unit contact stiffness of the wire is about 0.0033 N/mm. This law is the same as the stiffness model of machine tool [6]. Therefore, the contact stiffness of wire web could be obtained by multiplying the unit contact stiffness by the real contact area which is wire number, as shown in Eq. (2):

\[
K = N \times K_s
\]  

(2)

where \( K \) is the stiffness of wire web, \( K_s \) is the stiffness of single wire, and \( N \) is the number of wire forming wire web.

### 4.2 Static stiffness matrices of wire web

The incremental static stiffness of diamond wire web is defined as the load force required to cause the same amount of
deformation. The equation is shown in Eq. (3). The incremental static stiffness of a single diamond wire forming the wire web is expressed as Eq. (4):

$$K_i = \frac{(F_n - F_p)}{(D_n - D_p)}$$

$$K_{is} = \frac{K_i}{N}$$

where $K_i$ is the incremental stiffness of wire web; $F_n$ and $F_p$ are the load of the next position and the previous position, N; and $D_n$ and $D_p$ are the deformation of wire web on the next position and the previous position, mm. $K_{is}$ is the incremental stiffness of single wire.

The stiffness matrix between the average incremental static stiffness of a single diamond wire and the number of wires forming the wire web and the feed position is shown in Fig. 8a. The feed position and wire number are independent variables as the vertical axes and horizontal axes displayed in the graph coordinates, while the stiffness of single wire is a dependent variable expressed by color cloud image with numerical value. With the increase of wire number, the average incremental static stiffness of a single wire decreases slightly; with the increase of the feed position corresponding to wire bow, the incremental static stiffness of a single wire increases greatly.

The stiffness matrix of the incremental static stiffness of the whole wire web with the number of wires and the feed position is shown in Fig. 8b. With the increase wire number, the stiffness of wire web increases. With the increase of feed position, the tension in the wires increases, and the stiffness of the wire web per unit feed distance increases.

It can be concluded that:

1. Under the condition of the same machine tool, wire, and machining technology, the increasing wire number will greatly improve the stiffness of the wire web, and the stiffness of a single wire decreases slightly, which indicates that increasing wire number is helpful to improve the stiffness of the wire web and reduce the loading of a single wire.

2. With the increase of wire bow, both the stiffness of the whole wire web and the stiffness of a single diamond wire will be greatly increased, and the increasing trend will gradually increase. But this will increase the loading of diamond wire, which is easy to cause wire broken.

### 4.3 Relationship between static stiffness of wire web and wire bow during sawing

The relationship between the wire bow and its corresponding static stiffness of wire web calculated by the actual sawing kerf is shown in Fig. 9. The wire bow can be stable only when the number of wire forming wire web is more than 20. With the increase of the wire number from 5 to 10, the stiffness of wire web increased, and the corresponding wire bow decreased significantly. However, when the number of wires increases from 10 to 15 and from 15 to 20, the phenomenon is different at different feed positions with wire bow decreases or increases irregularly. However, as the number of wires

![Fig. 3 Silicon workpiece used in the test and sawing kerf](image1)

![Fig. 4 Measuring forces in the stiffness test of wire web with different number of wire](image2)
continues to increase, the wire bow begins to stabilize. With the stiffness of the wire web continues to increase, the wire bow will not change significantly with the increase of stiffness. It shows that one of the conditions to ensure stable sawing is that the number of wire web should exceed at least 20.

The more the number of wires, the higher the stiffness and the higher the stability of wire deformation. If the stiffness in Fig. 9 is more than 3 N/mm, the wire bow can be stably predicted for the wire web composed of more than 20 wires. The wire bow corresponding to the number of wire can be seen that the wire bow of 5, 10, and 15 fluctuates greatly.

It can also be seen from the proportional coefficient between the kerf length $l_k$ and the preset sawing length $l_p$ in Fig. 10 that the proportion coefficient $l_k/l_p$ changes when 5, 10, and 15 wires form a wire web. Only when more than 20 wires form the wire web, the proportion coefficient between the actual sawing length and the preset sawing length can be stable, that is, when the sawing length is set, the stable sawing length can be output, which is helpful for ensuring and predicting the sawing accuracy.

The stiffness of wire web can be obtained by calculating the force along the feeding direction of silicon ingot and the preset feed position during cutting, as Fig. 11a shown. It can be seen that the deformation of wire web is also proportional to the feed force during sawing, and the cutting stiffness in Fig. 11b is close to linear with the number of wire that forming wire web.

4.4 Machining accuracy due to wire bow

When the wire is deformed under the action of forces, it will generate wire bow. Wire bow $h$ is one of the main factors that affect the wire machining accuracy. In the cutting test in Table 2, the wire is set a preset feed distance which is defined as theoretical sawing length $l_p$, as shown in Fig. 12. The wire will deform during the sawing process due to wire bow, and the actual length of kerf after sawing is defined as kerf length $l_k$. The wire bow on the sides of silicon ingot can be calculated from the sawing length and kerf length, that is, $l_p - l_k$. As the difference $\Delta l$ between the wire bow on the sides of silicon ingot $l_k$ and the wire bow in the cutting zone $l_p - l_k + \Delta l$ is very small, the difference $\Delta l$ can be ignored. The wire bow $h$ is

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**Fig. 5** Stiffness of wire web composed of multiple wires

**Fig. 6** The lateral force and force on the wire cutting direction vary with the feeding pressure and the number of wires that forms wire web (a lateral force; b force in the cutting direction)

**Fig. 7** The relationship between the stiffness of wire web and the number of wires

It can be explained from the static stiffness of the wire web and the cutting stiffness of the wire web. For the multi-wire sawing machine, the wire web must contain at least 20 wires to ensure enough stiffness of wire web and can obtain stable cutting accuracy. For single wire and a small number of wire sawing machine, it can realize the rewinding of diamond wire or the arrangement of multi-wheel from the aspect of machine tool design, which is beneficial to ensure the stiffness and accuracy and reduce the wire bow and machining error.
directly obtained from the kerfs measurement data $l_k$ on both sides of the silicon ingot, approximately.

The wire bow means insufficient machining that could induce loss of machining accuracy. Low wire stiffness could easily cause wire deformation and then induce wire bow. For example, as shown in Fig. 12, when the preset sawing distance is $l_p$, but the actual sawing distance is $l_k$, the loss of machining accuracy in the feed direction of the wire is $l_p - l_k$.

For the lateral direction perpendicular to the wire feed direction, the diamond wire is deformed laterally due to the action of the lateral force and then deviates from the theoretical position, resulting in the lateral machining error. Generally, the drum error is the main performance in the silicon sawing, that is, the size error generated in the diamond wire sawing in and sawing out position is less than the middle position in the cutting process. This is because the diamond wire is more likely to produce larger lateral force due to the poor cooling conditions and the cumulative effect of the wire bow in the middle of the silicon ingot. On the premise of a certain lateral stiffness of diamond wire, a larger lateral force corresponds to a larger lateral deformation.

Fig. 13 provides the relationship between the wire bow and the number of wires that make up the wire web. In this figure, the preset feed position means the sawing distance from the experiment design as shown in Table 2, while the wire bow is measured and calculated by the kerf length as shown in Fig. 3. When the number of wires is 5, 10, and 15, the change of wire bow fluctuates with the change of feed position. The maximum wire bow of 5 wires is 2–4.2 mm, while that of 10 wires is 2–4.15 mm, and that of 15 wires is 1.5–3 mm. When the number of wires is 20, 30, and 40, the difference of wire bow is not big under the same feed position, the wire bow is stable.
at about 2.5 mm, and the maximum difference of wire bow is not more than 0.5 mm.

4.5 Finite element analysis of wire deformation

4.5.1 Finite element model

The static stiffness test is carried out on the finalized equipment of GC630S, but it is inconvenient to change the structure after the equipment is finalized. As the wheel span and wheel diameter affect the stiffness of wire web, the finite element method is used to make qualitative analysis. The variable parameters of FEM are shown in Table 3.

The analysis results of wire web deformation on the condition of wheel span 500 mm, wheel diameter 218 mm, wire tension 10 N, and contact length 1/4 winding circle are shown in Fig. 14. Under the preset tension and the uniformly distributed load shown in Fig. 14a on the diamond wire, the deformation along the loading direction is generated to form wire bow as shown in Fig. 14b and c.

4.5.2 Influence of wheel span, wheel diameter, and tension on wire deformation

The effects of wheel span, wheel diameter, and preset tension on wire stiffness are shown in Fig. 15. With the increase of wheel span, the deformation of wire web increases greatly, and the stiffness of wire web decreases sharply. Among the three selected wheel diameters of 180 mm, 218 mm and 250 mm, the wire deformation of wheel diameter of 218 mm is the smallest, and the stiffness of wire web is the best. The larger the preset tension of diamond wire, the smaller the wire deformation and the better the stiffness of wire web.

Therefore, reducing the wheel span and increasing the preset tension on the diamond wire are very helpful to improve the stiffness of wire web. There is an optimal range of wheel diameter for improving the stiffness of wire web. It is not that the larger or smaller the wheel diameter is, the better the stiffness of the wire web is.

4.5.3 Stiffness evaluation of wire web

Wu [17] proposed three performance indices for stiffness evaluation to investigate the stiffness of 5-DOF machine tool changing along different directions with a given machine configuration. In this paper, the evaluation indices are used to evaluate the stiffness of wire web changing with wheel span, wheel diameter, and preset tension.

1. $C_1$: the lowest stiffness
2. $C_2$: the ratio of the highest stiffness to the lowest stiffness
3. $C_3$: the average stiffness
The minimum deformation of the wire web is 0, so evaluation index of C2 is not considered. Indexes of C1 and C3 are used to evaluate. The results of the evaluation are consistent with the overall distribution trend. The significance of the evaluation indexes is in the stiffness comparison of diamond wire sawing machine tools with different design parameters, such as machine tools produced by different manufacturers, different specifications, different design parameters, and different parts and components. In Fig. 16a, the average stiffness is used for the comparison and evaluation of diamond wire sawing machine tool with different wheel span. It can be seen that the deformation of wire web with larger wheel span is greater. So the stiffness of wire web is worse. In Fig. 16b, through the comparison of the average stiffness, it is found that when the guide wheel diameter is 218 mm, the deformation of wire web is better than the guide wheel diameter of

**Table 3 Test parameters of finite element analysis**

| No. | Wheel span $L_w$, mm | Wheel diameter $D$, mm | Wire tension $F_T$, N | Contact length $l_c$, circle |
|-----|----------------------|-----------------------|----------------------|-----------------------------|
| 1–3 | 370, 500, 637        | 218                   | 10                   | 0.25                        |
| 4–6 | 637                  | 180, 218, 250         | 10                   | 0.25                        |
| 7–9 | 637                  | 218                   | 5, 10, 15            | 0.25                        |

**Fig. 14** Deformation of single wire with 1/4 winding contact length (a loads and constraints of FEM; b and c single wire deformation)
180 mm and 250 mm, indicating that the corresponding stiffness of wire web is better. In Fig. 16c, through the evaluation of the average stiffness, it can be found that the greater the preset tension, the greater the stiffness of wire.

5 Conclusion

In this paper, the definition of stiffness of wire web was proposed, and it is considered one of the indexes that determine the machining accuracy of DWS. The research can draw the following conclusions:

1. The linear relationship between wire deformation and loading force was found. The definitions of static stiffness of wire web and cutting stiffness were proposed based on relationship. The measurement methods and evaluation standard of wire stiffness was provided. It is found the concept of wire stiffness could be used to evaluate the performance of wire sawing machine tool.

2. The static stiffness matrix of the wire web and the single wire was provided by a series of stiffness test. The experimental results show that the number of wires in the wire web cannot be less than 20 in order to ensure enough machining accuracy and make it stable and predictable. Measures that increase wire number such as wire rewinding and adding guide wheel could improve the stiffness of wire web and further improve the machining accuracy.

3. By establishing the correlation analysis of wire bow and wire stiffness, it is found that better stiffness of wire web could improve the machining accuracy of diamond wire saw and reduce wire bow and its corresponding forces.

4. A finite element method was established to analyze the influence of multiple parameters on the wire web stiffness. It is found that reducing the wheel span and increasing the preset tension of wire could improve the stiffness of wire web. An optimal range of wheel diameter for improving the stiffness of wire web existed.
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Data availability All allowed data has been provided in the manuscript.

Declarations

Ethical approval This work has no research involving human participants and/or animals.

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References

1. Holt A, Thogersen A, Rohr C (2010) Surface structure of monocrystalline silicon wafers produced by diamond wire sawing and by standard slurry sawing before and after etching in alkaline solutions. Photovoltaic Specialists Conference (PVSC). https://doi.org/10.1109/PVSC.2010.5614103
2. Wu H, Melkote SN, Danyluk S (2012) Mechanical strength of silicon wafers cut by abrasive slurry and fixed abrasive diamond wire sawing. Adv Eng Mater 14(5):342–348
3. Wu X, Tan Y, Li J (2020) Surface damage and metal-catalyzed chemical etching investigation of multicrystalline silicon by diamond wire sawing. Sol Energy 207:609–617
4. Xiao H, Wang H, Yu N (2019) Evaluation of fixed abrasive diamond wire sawing induced subsurface damage of solar silicon wafers. J Mater Process Technol 273:116267
5. Suzuki T, Nishino Y, Yan J (2017) Mechanisms of material removal and subsurface damage in fixed-abrasive diamond wire slicing of single-crystalline silicon. Precis Eng 50:32–43
6. Kono D, Inagaki T, Matsubara A (2013) Stiffness model of machine tool supports using contact stiffness. Precis Eng 37(3):650–657
7. Sarenac M (1999) Stiffness of machine tool spindle as a main factor for treatment accuracy. The Scientific Journal of FACTA Universitatis 1(6):665–674
8. Yen JY, Chang HM (2004) Performance robustness and stiffness analysis on a machine tool servo design. Int J Mach Tool Manuf 44(5):523–531
9. Li B, Hong J, Liu Z (2014) Stiffness design of machine tool structures by a biologically inspired topology optimization method. Int J Mach Tool Manuf 84:33–44
10. Majda P, Jastrzębska J (2021) Measurement uncertainty of generalized stiffness of machine tools. Measurement 170:108692
11. Laspas T, Theissen N, Archenti A (2020) Novel methodology for the measurement and identification for quasi-static stiffness of five-axis machine tools. Precis Eng 65:164–170
12. Huang TY, Lee JJ (2001) On obtaining machine tool stiffness by CAE techniques. Int J Mach Tools Manuf 41(8):1149–1163
13. Matsubara A, Tsujimoto S, Kono D (2015) Evaluation of dynamic stiffness of machine tool spindle by non-contact excitation tests. CIRP Ann Manuf Technol 64:365–368
14. ASME B5.54 Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers, 2005.
15. Karmakar N, Chetikena H, Venkateshwaran M (2020) Direct wire-tension measurement based bowing correction in hot wire cutting of polystyrene. Procedia Manuf 48:230–236
16. Qiu J, Li XF, Ge RP (2020) Formation mechanism of wire bow and its influence on diamond wire saw process and wire cutting capability. Int J Mech Sci 185:105851
17. Wu J, Wang JS, Wang LP, Li TM, You Z (2009) Study on the stiffness of a 5-DOF hybrid machine tool with actuation redundancy. Mech Mach Theory 44:289–305

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