Development of a Shock & Vibration Spec for 300mm Wafer AMHS Handling

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Abstract

In this work, a technique is presented for establishing and verifying safe vibration and shock limits for preventing cross-slotting of 300mm wafers in FOUPs during AMHS handling. This technique includes establishing the safe limits using a shaker table, calibrating these limits for a particular portable accelerometer, and then using this portable accelerometer to check an AMHS for compliance to these limits.

Keywords

300mm semiconductor automation, AMHS, shock, and vibration.

INTRODUCTION

The requirements for 300mm semiconductor manufacturing have led to increasing levels of automation. This automation includes Automated Material Handling Systems (AMHSs) for moving and storing wafers between process steps in Front Opening Unified Pod (FOUP) mini-environments. These AMHSs for interbay and intrabay transport include vehicle-based systems on overhead rails, Automatic Guided Vehicles (AGVs), and conveyors. Automated Storage and Retrieval Systems, also known as stockers, are used for storing the wafers between process steps.

Due to the high costs (time and money) of manufacturing production and test lots, limits on vibration and shock are specified for automated FOUP handling to prevent damage to the wafers. A FOUP is a SEMI E47.1 [1] compliant box with a SEMI E1.9 [2] compliant non-removable cassette for holding 25 or less wafers. Wafers are simply supported on their edges using individual wafer supports in the horizontal axis. When a FOUP is exposed to excessively rough handling conditions causing a wafer to bend, the flexibility in the wafer can cause the wafer to slip from its support and land on a wafer below. This contact between the wafers can cause damage to the top surfaces containing product layers and also prevents correct wafer extraction by front end tool robots at process tools.

Handling conditions can be characterized in terms of vibration and mechanical shock. Vibration is steady state oscillation of the FOUP, typically characterized in terms of Root Mean Square (RMS) averages over some time period versus time. Vibration can also be characterized in terms of Power Spectral Density (PSD) energy versus frequency using a Fourier Transform to convert data collected over time into the frequency domain. Mechanical shock is a singular, transient event caused by a drop, collision, or excessive jerk (time derivative of acceleration) of a FOUP over a few tens of milliseconds. Shock events can be characterized in terms of a peak acceleration and a change in velocity [3]. Vibration and shock levels are typically proportional to AMHS handling speeds. Excessive vibration and shock can be caused by the AMHS design, AMHS installation problems, mechanical wear or slippage in AMHS components, or external environmental changes such as shifts in the building structure. It is useful to maximize the vibration and shock limits with the constraint of preventing damage to the wafers. This enables AMHS vendors to optimize throughput, cycle time, and cost of AMHS products without causing damage to wafers.

CURRENT PRACTICE IN INDUSTRY AND LIMITATIONS

The current industry practice for specifying limits on FOUP handling conditions includes collecting vibration data from FOUPs handled by an installed, baseline AMHS that is not adversely affecting product yields. This can be done by mounting an acceleration recording device in a FOUP handled by the AMHS. Due to memory constraints, these recording devices may not record all measured acceleration data over a test period of 30 minutes or longer. Instead, these recording devices record averaged RMS vibration values over time. Time-stamped RMS vibration values can be related to specific AMHS events (e.g., pickup, travel, dropoff) using time-stamped observations of the AMHS or AMHS data logs. The RMS upper limits from measurements on the baseline AMHS can be compared with RMS upper limits on new AMHS products for product certification. These RMS baseline upper limits can also be compared to RMS upper limits on installed AMHS products to check for mechanical wear/slippage or external environmental changes.

Limitations of this current industry practice are that the established limits for handling conditions will tend to be lower than necessary to prevent damage to the wafers. This can prevent innovations by AMHS vendors to optimize throughput, cycle time, and cost of AMHS products. The reasons for these unnecessarily lower limits are as follows. (1) The baseline AMHS is probably not optimized to handle FOUPs at a maximum speed with the constraint of preventing damage to the wafers. (2) RMS vibration data in the time domain does not characterize energies at particular frequencies. Wafers in a FOUP that is vibrated at a particular energy level at the resonant frequency of the wafers will oscillate at a much higher level than wafers in the FOUP that is vibrated at the same energy level at a frequency away from the resonant frequency. Thus, safe thresholds for RMS must be lower than necessary to include the possibility of vibrating the FOUP at a frequency close to the wafer resonant frequency. (3) A shock event over a millisecond time period will be averaged into a RMS average over a longer time period, typically 0.5 second or more. Thus, depending on the time period of the RMS averages, safe thresholds for RMS must be lower than necessary to include these shock events.

PROPOSED SOLUTION

To address these limitations, the authors tested a particular type of FOUP using standard mechanical test methods [3, 4] with a vertical shaker table to determine safe thresholds for frequency domain vibration and transient shock on the shaker in the vertical axis to avoid wafer cross-slotting. Given these safe thresholds on the shaker, the response of a portable accelerometer to these safe thresholds can be measured and compared with the response of the portable accelerometer to actual handling by an AMHS to check for safe handling conditions.

This approach is similar to the approach taken by the hard disk drive industry that specifies vibration and shock limits for hard drives in terms of vibration and shock levels on a shaker table [9]. The response of a portable accelerometer to these hard drive vibration and shock limits must be measured on the shaker table first before determining if a particular environment is safe for a hard drive.

Vibration Testing

During this testing, the FOUPs were simply supported on the shaker table using SEMI E57 [7] compliant kinematic coupling pins to emulate a typical method for securing FOUPs to AMHSs. The controller for the shaker table can be programmed to generate a specific frequency waveform or specific shock pulses and uses an uniaxial, teardrop accelerometer on the table surface for feedback.

The authors first followed the test method B from ASTM D3580-95 [4] to identify the resonant frequencies of wafers in the FOUPs. This involved shaking FOUPs using a flat input PSD waveform from the shaker table and teardrop, uniaxial accelerometers mounted to the middle of the wafers to record the acceleration responses of the wafers. Subsequently, the time history of the accelerations was automatically converted into a frequency response using a Fourier transform. The authors investigated resonant frequencies of the wafers in the vertical axis only. Multiple FOUPs were tested with differing numbers of wafers. Experimental results indicate resonance behavior around 30 Hz and 100 Hz (see Figure 1).

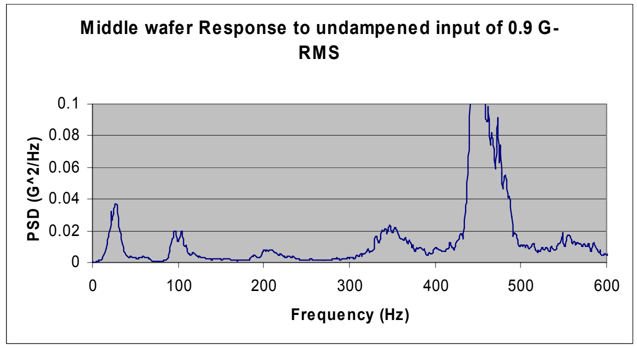

Figure 1

Next, the authors generated a new input frequency waveform for the shaker table with lower vibration energy levels around the first two resonant frequencies. Multiple tests were performed with slowly increasing energy levels of this input waveform until wafer motion began to approach a maximum acceptable level. The authors then performed multiple tests of this dampened input waveform (Figure 2) with different FOUPs and different numbers of wafers to ensure that no wafer cross-slotting occurs with this input waveform.

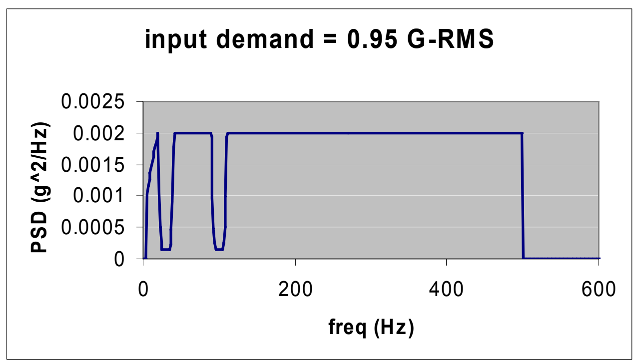

Figure 2

The resulting frequency response to the dampened waveform shows the resonance peaks dampened (Figure 3) in comparison to the response to the flat input waveform of Figure 1.

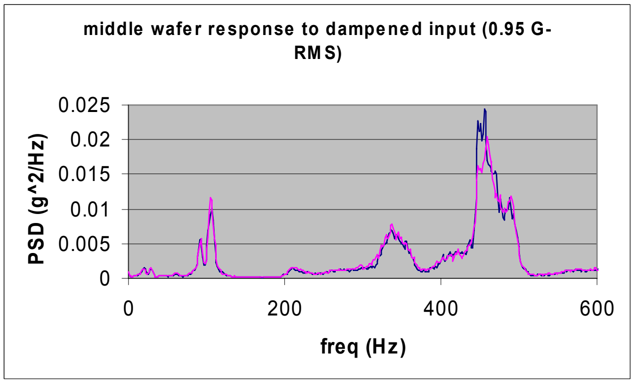

Figure 3

Shock Testing

The authors followed the test procedures of ASTM D3332-99 [3] to determine a wafer cross-slotting threshold in terms of the peak acceleration and velocity change in the vertical axis. The focus of this work is on sensitivity to vertical shock because horizontally mounted wafers are most sensitive to vertical shocks. This technique could also be applied to determine horizontal shock limits using a horizontal shaker table. For a shock event described by an acceleration waveform over time, the peak acceleration is the highest point of the waveform and the velocity change is the area of the waveform. An input shock pulse to a physical system theoretically must have a critical velocity change and a critical peak acceleration in order for a component in the system to fail [10]. The vertical shaker table used for these experiments is capable of creating shock pulses using either half-sine or trapezoidal acceleration waveforms with a pre-shock pulse up to 5% of peak acceleration and a post-shock pulse up to 20% of peak acceleration. As with the vibration testing, the FOUPs were simply supported on the shaker table using SEMI E57 [7] compliant kinematic coupling pins to emulate a typical method for securing FOUPs to AMHSs.

ASTM D3332-99 specifies test methods A and B to identify a safe velocity change value and a safe peak acceleration value that define a damage boundary. In general, this damage boundary marks an unsafe region in the space of velocity change versus peak acceleration. For FOUPs with wafers, this unsafe region marks combinations of velocity change and peak acceleration that result in cross-slotting of wafers. Shock events with velocity change and peak acceleration values that are to the left or below this damage boundary should be safe from wafer cross-slotting.

The authors used test method A to determine the safe velocity change for the FOUPs with wafers. Test method A consists of shaking a FOUP with wafers with a half-sine acceleration waveform having slowly increasing values of velocity change and constant pulse width until cross-slotting occurs. For each value of velocity change, the FOUP was shaken 20 times with 10 seconds' pause between each shock pulse and then inspected for cross-slotting. For all values of velocity change V_{change}, the pulse duration T_p was set to 3 milliseconds according to the guidelines of test method A and the peak acceleration A_{peak} was set based on calculations from increasing values of velocity change. Specifically, through integration of the half sine waveform (assuming a perfect waveform),

$$A_{peak} = \frac{\pi * V_{change}}{2 * T_p}$$

After testing with multiple FOUPs and different numbers of wafers in the FOUPs, this test resulted in a safe velocity change value of 5.18 inches/sec as the last measured point before wafer cross-slotting could occur at 5.31 inches/sec. Figure 4 shows the velocity change versus acceleration test values for Test Method A, and the resulting safe velocity change boundary at 5.18 inches/sec (with peak acceleration of 6.94 G).

The authors used test method B to determine the safe peak acceleration for the FOUPs with wafers. Test method B consists of shaking a FOUP with wafers with a trapezoidal acceleration waveform having slowly increasing peak acceleration values with constant velocity change until cross-slotting occurs. The trapezoidal waveform is used as a "worst case" waveform to provide a safety factor. For each value of peak acceleration, the FOUP was shaken 20 times with 10 seconds' pause between each shock pulse and then inspected for cross-slotting. For all values of peak acceleration, the velocity change was set to 1.57 times the safe velocity change value identified in test method A or 8.04 inches/sec. The trapezoidal waveform was programmed to have rise and fall times of 1.8 milliseconds.

After testing with multiple FOUPs and different numbers of wafers in the FOUPs, this test B resulted in a safe peak acceleration value of 1.8 G as the last measured point before wafer cross-slotting could occur at 1.9 G. Figure 4 shows the velocity change versus acceleration test values for Test Method B and the resulting safe peak acceleration boundary at 1.8 G (and velocity change of 8.04 inches/sec).

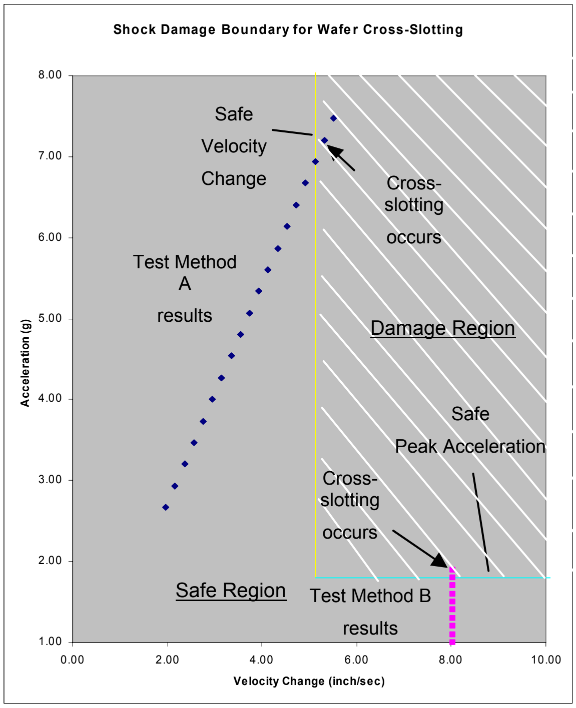

Figure 4

Safety of Vibration and Shock Limits

These proposed vibration and shock limits are based on testing multiple FOUPs with different numbers of wafers on a shaker table for cross-slotting. As another check on the safety of these vibration and shock limits, the authors measured the planar stress levels on the top and bottom surfaces of wafers inside FOUPs shaken at the proposed vibration and shock limits. These resulting stress levels can be compared with stress levels determined to fracture wafers.

Accordingly, the authors attached a 45 degree strain gauge rosette to a surface of a [100] Silicon wafer, placed the instrumented wafer into a FOUP, placed the FOUP on the shaker table, and recorded the strain measurements during shaking of the FOUP at the proposed vibration and shock limits.

The 45 degree strain gauge rosette with measured strain vector $\{E1, E2, E3\}$ was attached to the wafer according to Figure 5.

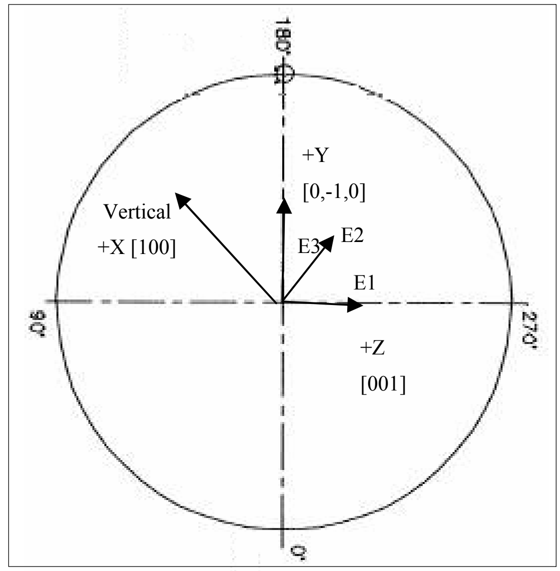

Figure 5

According to standard strain transformation calculations [8], the 45 degree strain gauge rosette measurements are transformed to align with the wafer coordinate system as follows.

$$\varepsilon_1 = planar\ strain\ along\ X\ axis\,[100] = 0$$
$$\varepsilon_2 = planar\ strain\ along\ Y\ axis\,[010] = E3$$
$$\varepsilon_3 = planar\ strain\ along\ Z\ axis\,[001] = E1$$
$$\varepsilon_4 = planar\ strain\ in\ plane\ defined\ by\ Y, Z\ axes$$
$$\varepsilon_4 = 2 * E2 - (E1 + E3)$$
$$\varepsilon_5 = planar\ strain\ in\ plane\ defined\ by\ X, Z\ axes$$
$$\varepsilon_6 = planar\ strain\ in\ plane\ defined\ by\ X, Y\ axes$$

A stiffness tensor can be used to transform strain measurements into stress values. A commonly used C_{ij} stiffness tensor for Silicon that is aligned with the [100], [010], and [001] crystal directions is as follows [5].

$$C_{ij} = \begin{bmatrix} 166 & 64 & 64 & 0 & 0 & 0 \\ 64 & 166 & 64 & 0 & 0 & 0 \\ 64 & 64 & 166 & 0 & 0 & 0 \\ 0 & 0 & 0 & 80 & 0 & 0 \\ 0 & 0 & 0 & 0 & 80 & 0 \\ 0 & 0 & 0 & 0 & 0 & 80 \end{bmatrix}$$

The authors measured strain values of 8.1E-5% along the [010] axis, 1.6E-5% along the [001] axis, and 1.7E-5% about the [100] axis. After transforming the strain values using the C_{ij} stiffness tensor, the following stress values were calculated: 6.2 MPa along the [100] axis, 14.5 MPa along the [010] axis, 7.8 MPa along the [001] axis, and 1.4 MPa about the [100] axis.

These stress values compare favorably with static fracture stress values for Si and product layers. For example [6] reports a failure probability of 0.03 at 275.27 MPa with a

3-point bend test for a silicon daisy chain (SiDC) die used in flash memory packages.

Other factors, outside of the scope of this paper, may also be relevant in determining the safety of the proposed vibration and shock limits such as particle generation and microfracturing of product layers.

Accelerometer Calibration

The authors next characterized the vibration and shock responses of a particular accelerometer-recorder bolted to a particular FOUP based on the proposed vibration and shock limits on the shaker table in order to have a baseline for determining safe handling conditions on an AMHS. This baseline comparison assumes that the same combination of the accelerometer-recorder, the FOUP, a means for bolting the accelerometer to the FOUP, and a specific number of wafers located in specific slots of the FOUP used to establish this baseline will also be used to determine safe handling conditions on an AMHS.

In general, accelerometer-recorders need to meet certain requirements to determine safe handling conditions according to the proposed vibration and shock limits. These requirements include the capability to continuously record acceleration data in the vertical axis with sufficiently high sampling rate so that frequency domain data may be extracted. Naturally, some means must be provided to calculate the frequency domain data. Another requirement is the capability to take the upper limit of the frequency domain data from the waveforms over time. Another requirement is the capability to analyze the time history of the acceleration data to extract shock metrics such as peak acceleration and velocity change. The accelerometer and its analysis software for meeting these requirements must be identical while determining the baseline safe handling limits for vibration and shock and when determining safe handling conditions on an AMHS.

One issue is how to compare vibration frequency domain waveforms collected over multiple time domain periods on the AMHS with the accelerometer response to the input threshold waveform from shaker table. The authors chose to use the "upper limit rule" for this comparison. With this technique, the upper limit of PSD values for frequency slices from frequency domain waveforms from multiple time domain periods during handling by an AMHS should be lower than upper limit of PSD values measured from the accelerometer's response to the input vibration limit waveform from the shaker table.

First the authors characterized the particular accelerometer's upper limit response on a FOUP to the input vibration limit waveform from the shaker table. The FOUP was loaded with 16 wafers. Figure 6 shows this upper limit response in the frequency domain.

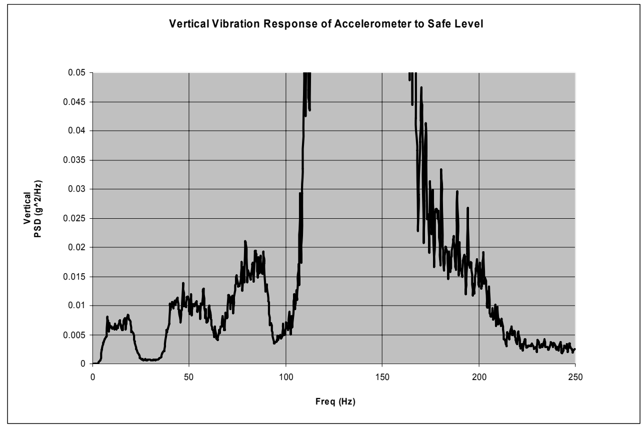

Figure 6

The advantage of this upper limit comparison technique is that only the worst case (upper limit) energies at each frequency value over time are used for this comparison. The disadvantage of this technique is that the frequency domain data is typically noisy and it is unclear what the best methods are for establishing a safety tolerance around the upper limit data for this comparison.

The authors then measured the particular accelerometer's shock response to the safe velocity change limit (5.18 inches/sec) and peak acceleration limit (1.8 G) on the shaker table previously determined for shock. Responses were measured for two shock event-types: (1) a half sine waveform with a velocity change of 5.18 inches/sec and peak acceleration of 6.94 G, and (2) a trapezoidal waveform with a velocity change of 8.04 inches/sec and peak acceleration of 1.8 G. Figure 7 shows the responses from these two shock events and a damage boundary for this accelerometer in the velocity change-peak acceleration space. The authors chose the safe velocity change limit for this accelerometer to be the maximum of the velocity change values from the responses to the first event type, resulting in a safe velocity change limit of 2.34 inches/sec. The authors chose the safe peak acceleration limit to be the maximum of the peak acceleration values from the responses to the second event type, resulting in a safe peak acceleration limit of 3.15G.

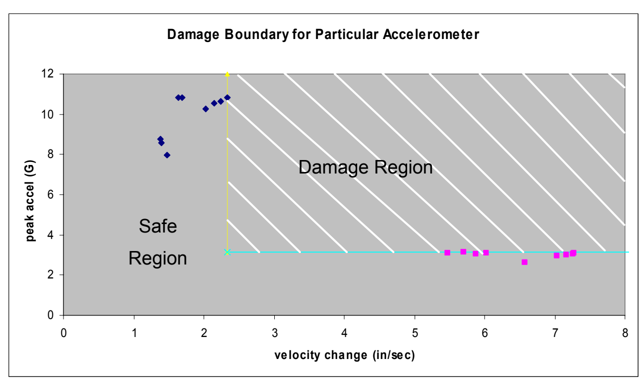

Figure 7

AMHS Testing

Given these vibration and shock limits defined for the particular accelerometer/FOUP configuration, an AMHS can now be tested for safe handling conditions. The AMHS could be set up to move around the FOUP with the accelerometer and the subsequent vibration and shock responses could be compared with these limits.

For example, during the evaluation of an AMHS, a recorded peak at a particular frequency from the frequency analysis that is significantly higher than the upper limit response shown, for one example, in Figure 6, indicates that the FOUP is being vibrated with excessive energy at that frequency. In this case, the time history of the frequency data should be analyzed with respect to the AMHS event history to identify which states or locations of the AMHS contributed to the excessive energy at that frequency. Next, the AMHS could be tuned or redesigned to dampen out that frequency at the appropriate states or locations.

For another example, during the evaluation of an AMHS, a recorded shock event that is well within the damage region shown, for one example, in Figure 7, indicates that something caused a significantly unsafe shock event. In this case, the time history of the AMHS should be analyzed with respect to the AMHS event history to identify which state or location of the AMHS contributed to the shock event. Once identified, the AMHS could be tuned or redesigned to either remove the shock event or cushion the system to lower the shock levels.

In addition to enabling simple compliance to the vibration and shock limits, this detailed feedback for the AMHS design enables greater awareness of the constraints of the design, allowing for increased optimization of AMHS performance. For instance, it is possible that the speed of an AMHS could be increased with this greater awareness of the particular frequencies that need to be dampened out. Similarly, the greater awareness of the shock limits could also increase the speed of an AMHS by cushioning or removing particular shocks in the system. Increasing the speed of an AMHS typically enables direct improvements in the throughput and cycle time of AMHSs. Furthermore, given a set of fixed performance requirements for an AMHS, these improvements should decrease the overall cost for the AMHS as performance increases.

CONCLUSION

A technique for establishing and verifying safe vertical vibration and shock limits for preventing cross-slotting of 300mm wafers in FOUPs during AMHS handling has been presented. This technique includes establishing the safe limits using a shaker table, calibrating these limits for a particular portable accelerometer, and then using this portable accelerometer to check an AMHS for compliance to these limits. If an AMHS does not comply with these limits, the detailed feedback about excessive energy at a particular vibration frequency or excessive shock levels should enable the AMHS to be redesigned into compliance. Furthermore, given this feedback, AMHS vendors can optimize the throughput, cycle time, and cost of AMHS products with the constraint of these clearly defined safe wafer handling conditions.

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BIOGRAPHY

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