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Mechanical Testing of Miniature Parts, Techniques, and Methods: A Review

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Abstract

Micro component testing has become increasingly popular over the last twenty years, largely due to the reduction in system and device sizes. The continuous evolution of technologies such as medical and bioengineering, microelectromechanical systems, and aerospace has imposed an imperative need to improve mechanical testing methods for small components. These industries need intricate and complex parts, which require improving the methods of testing to accommodate such small sizes. The latest review examines the current methods and techniques of mechanical testing of micro components, regarding their adaptation to incredibly small components. More than one hundred studies in this field were summarized and reviews the recent developments in the field of micro component testing, in addition to focusing on the methods and techniques used. In addition, highlighting future challenges and research paths that contribute to the development of these technologies were highlighted. These insights offer valuable guidelines for researchers, engineers, and technologists working in precision manufacturing, such as micro-electro-mechanical systems (MEMS), electronics, semiconductors, and biomedical device development. Future work can focus on destructive and non-destructive testing methods, associated with computational modeling.

Keywords: Micro parts, Micro mechanical testing, In-situ micro/nano mechanical testing, Micro-scale load and displacement characterization.

1. Introduction

The continuous progress in the development of miniaturized technologies has revolutionized numerous fields such as microelectronics, medical devices, MEMS, aerospace, and optoelectronics [1], [2]. Micro-scale, reliable, and accurate mechanical testing has become increasingly required in the past two decades due to the continuous miniaturization of instrument sizes. These mechanical tests have gained much attention in recent years due to their advantages in materials development. As components continue to be downsized, emphasis will be placed on interactions between mechanical properties and how mechanical loads affect the functional properties of materials [3] [4]. However, the innovation of a small-scale testing of parts faces various difficulties, such as the effects of size and handling on measurement, requiring the adaptation and development of testing systems [5].

The development of testing techniques and devices is aimed at understanding how the mechanical properties of materials change when their dimensions or internal property parameters are significantly altered [6]. The tailored micro-scale testing, such as tensile, compression, nanoindentation [7], dynamic mechanical analysis (DMA) [8], and digital image correlation (DIC) [9], contributes to the evaluation of the mechanical properties and ensuring the reliable and safe design of components [10]. The mechanical properties of radioactive metals, such as yield strength, modulus of elasticity, and fracture behavior, are typically studied using miniaturized mechanical testing techniques due to the difficulties associated with handling radioactive materials [11], radio alloys [12], and nanomaterials [13]. It is known that the geometric dimensions of a specimen significantly affect the results of mechanical tests, especially in composite materials and micro-scale tests [14]. The most prominent difficulties in miniaturized tensile, compression, and flexural tests are the need to apply special techniques and methods to ensure accuracy in measurements. D.S. Gianola and C. Eberl [15] noted that in micro-scale tensile testing, novel device designs have been introduced using miniaturized building parts such as nanocomposites ,micro electromechanical systems(MEMS) [16][17][18][19], nano electromechanical systems (NEMS) [20][21] , hybrid materials [22], nano-thin films [23][24] and nanowires [25][26][27] due to their outstanding properties. In micro-compression tests, there is a wide research focus on specimens measuring a few hundred micrometers, including the influence of specimen size, which has also received widespread attention from researchers [28][29][30][31] [32]. The most widely used method for compression testing utilizes a commercialized nano-tool and a modified Berkowitz tip, suitable for specimens with diameters of a few h undred micrometers or less [33][34][35][36][37][38]. The micro-flexural tests are used to measure the force required to bend a sample when subjected to specific loads. The data obtained are typically used to select materials that should withstand loads without failure in bending or flexing [39]. Determining flexural properties is of great importance in the fields of medicine, engineering, and dentistry, along with material applications such as fibers, glass, ceramics, and composites [40]. Understanding the deformation mechanisms and failure modes at micro- and nanoscales is essential for predicting the behavior of materials and inventing new materials with distinctive properties [41]. Several non-standard testing techniques for micro or miniaturized samples are currently available, designed to evaluate the mechanical properties of structural components and structures subjected to service in a non-destructive manner [42]. Much work is also being done to make micro-testing techniques standard testing techniques, which makes them acceptable to all concerned parties and enables them to benefit from its many advantages [43]. Recently, there has been increased focus on the production of micro-scale objects and the methodologies employing uniform miniature specimens, while preserving a critical advantage: the consistency of loading modes across micro-scale and full-scale specimens [44][45]. With continued progress, micro sample testing technology has reached its pinnacle of development [46]. Despite this progress, manufacturing of samples for mechanical testing, and high accuracy in measurements, generating force and displacement on a micro scale, are common challenges in mechanical testing in micro-scales [47].

This review article aims to provide a comprehensive overview of the current state of mechanical testing techniques, procedures, and methods for micro parts. It will review and discuss the principles, techniques, challenges, and limitations of these tests. Testing standards and several case studies are also considered, introducing a guide for researchers and engineers in selecting a suitable method for mechanical characterization of micro parts for different applications.

2. Challenges of Testing Micro Parts

Conventional mechanical testing methods for normal-sized materials often prove insufficient for micro parts, as they may lack the required sensitivity or introduce defects resulting from handling and clamping [48]. Precise mechanical characterization is essential to guarantee dependability, safety, and performance. The main challenges in mechanical testing at the micro/nano scale are preparing the sample and locating and treating it for testing, applying controlled amounts of force or displacement, in addition to accurately measuring stress and strain [49],[50]. Sample preparation is a factor that affects the accuracy and reliability of test results [51], as well as the determination of stress and strain, and micro tensile testing (MTT) techniques [52]. Due to the sample size and loading methods, small displacement measuring devices may be inaccurate, and this affects the displacement accuracy assessment[53]. In addition, sample alignment remains a challenge because the optical method of verifying sample alignment is not always guaranteed [54]. Therefore, one of the basic requirements for uniaxial testing is alignment between the specimen axis and the loading direction to ensure unified stress across the cross-section of the specimen. A slight misalignment may cause bending effects, and incorrect gripping may change the experimental results or demolish the samples, and Off-axis loading greatly affects the stress state of micro/nano-sized specimens and can result to significant errors in data analysis even when the deformity is in the elastic system [55],[56]. To identify potential sources and effects of misalignment, Kang and Seif looked loading scenarios for single axial tests. Figure 1 illustrates three possible misalignment faults of loading with respect to load direction. The first (Figure 1a) represents the ideal situation, where the specimen axis is perfectly aligned with the load direction, allowing for a uniform distribution of vertical stress without bending effects according to the relationship:

$$\sigma = \frac{f}{A} \qquad (1)$$

where σ is the stress, f is the applied load, and A is the cross-sectional area of the specimen.

The second case (Figure 1b) describes the transverse misalignment resulting from asymmetrical clamping, where a small eccentricity generates additional bending stress in addition to the axial stress. The total stress at a given point in the cross-section is calculated as follows:

$$\sigma_x = \sigma_U + \sigma_B = \frac{f}{A} + \frac{M_y}{I} \qquad (2)$$

where σ_U, $\sigma_B$are the uniaxial and bending stress, M is the bending moment due to the deflection, y is the perpendicular distance from the neutral axis, and I is the moment of inertia of the section. To quantify the non-uniform stress in the sample, a non-uniform stress error $\varepsilon_m$is defined as

$$e_{\mathrm{m}} = \frac{\sigma_{\mathrm{B}}}{\sigma_{\mathrm{U}}} = \frac{\varepsilon_{\mathrm{B}}}{\varepsilon_{\mathrm{U}}} \qquad (3)$$

Where ε_U and ε_B represent the strains induced by σ_U and σ_B, respectively. Since stress measurements are typically available on the sample surfaces, σ_B and ε_B are considered at the top or bottom of the sample.

In the case of transverse misalignment (Figure 1(b)), where the sample is subjected to a load f with eccentricity c due to asymmetrical sample fixation, the non-uniform stress error ε_A^{TM} can be expressed as:

$$\varepsilon_A^{TM} = \frac{\sigma_B}{\sigma_U} = \pm\frac{6c}{h}\frac{(\cosh\sqrt{f^*(\frac{2x^*-1}{2}})}{cosh\sqrt{\frac{f^*}{2}}} \qquad (4)$$

Where c/h represents the ratio of deflection to the height of the specimen, and f^*,x^* are normalized variables along the undeformed specimen

The third case (Figure 1c) addresses rotational misalignment that occurs when there is a small offset angle between the loading axis and the specimen axis, as in the case of nanowires. This can result in an asymmetric stress distribution, which results in stress concentration at the specimen's edges, particularly at the clamping points, affecting fracture strength measurements.

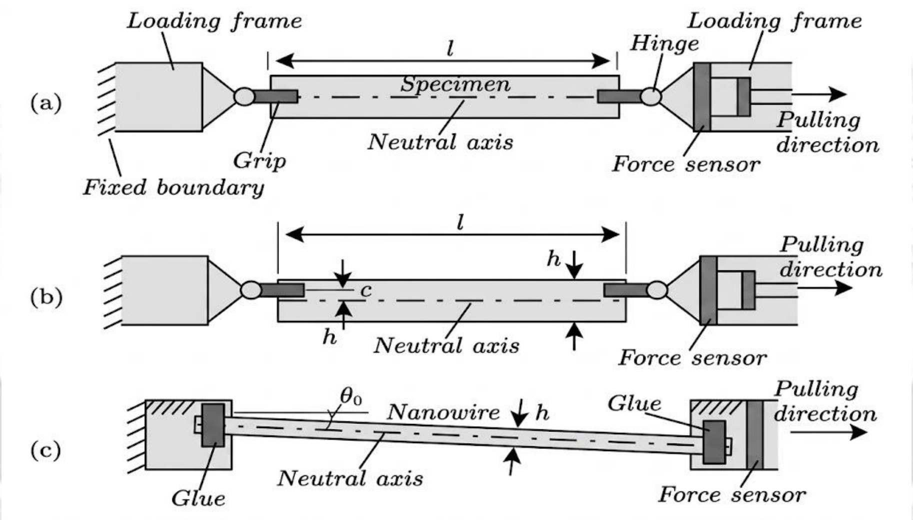

Figure 1. Scenarios of misalignment between loading and sample: (a) ideal loading alignment, (b) transverse misalignment, also(c) rotary misalignment [55]

On the other hand, biaxial testing at the micro- and nanoscale is challenging due to the difficulties in handling fine specimens and applying identical biaxial loads [57]. Another challenge is the lack of uniform geometries for micro tensile test specimens that yield data comparable to those obtained from standard tensile tests [58]. There is a significant degree of correlation between mechanical properties and specimen geometry [59]. Reducing the size of a tensile test specimen below the sub-volume level poses different challenges. These include specimen compliance with varying criteria of acceptance according to the standard test sample, the ratio of the width to the height, the least number of grains in the cross-section to achieve uniformity in metrological values, etc. [60] In micro compression testing, the most significant challenge is the specimen geometry itself. Kiener et al. [61] demonstrated that column dimensions, specifically the length-to-diameter ratio, have a direct impact on the deformation mechanism that occurs during loading. Very short columns prevent the development of significant slips, while long columns exhibit pre-yield buckling, which distorts the interpretation of yield strength and early plastic strain results. Another common challenge is the unevenness or tilt of the column base resulting from manufacturing, which can cause unwanted bending and distortion that affects the accuracy of elastic modulus and yield stress measurements. Accurate alignment and load distribution are among the most significant challenges in microbending tests. In a three-point bending test, a slight deviation from the vertical axis can produce an inhomogeneous stress distribution, affecting the results by reducing the accuracy of mechanical calculations such as the elastic modulus. Similarly, four-point bending requires a consistent axial distribution across two loading points; any slight shift or tilt at the loading points can distort the stress distribution and affect the results. Several studies have addressed the effect of size on the mechanical properties of materials, such as Zhu et al. [62] who noted that the resistance of materials to plastic deformation increases as their dimensions are reduced, they have not addressed alignment and load distribution issues in three-point/four-point bending tests, revealing a research gap.

3. Micro-Testing techniques

With the rapid advancement of microfabrication technologies and the integration of miniaturized components into various engineering applications, micro-tensile, flexural, and compression testing methods have emerged as essential tools for probing the mechanical response of dimensionally constrained materials. Recent studies have proposed a variety of refined techniques for testing micro-sized specimens, allowing accurate mechanical characterization at extremely microscales [63]. These microscales testing techniques enable the evaluation of mechanical properties such as strength, ductility, and stiffness in specimens in the range of nanometers, micrometers, and millimeters [64].

3.1. Micro-Tensile Testing Techniques (MTTs)

MTTs are among the most common micro-scale testing techniques (SSTT) [65], which have been widely developed recently to obtain the mechanical properties of small-sized materials such as microfibers, thin films, and nanowires. These techniques rely on the design of small devices and advanced measuring instruments to apply loads and measure strains accurately on micro-samples. These studies include a variety of materials under study, from thin films to micrometals and biomaterials. Among these studies, Nozawa et al. [66] proposed a technique based on digital image correlation (DIC). This technique was applied to stainless steel (RAFM), for example, F82H steel, which is the preferred structural material for molten vessel components in Japan. A flat rectangular microscope specimen of type SS-J3(Figure 2) was used to evaluate the neutron tensile properties under both irradiation and non-irradiation conditions. Pantano et al. [67] designed a MEMS system for in situ tensile testing of silver nanowires inside a scanning electron microscope (SEM) and demonstrated its efficiency with high control accuracy. Zhao et al. [68] used the finite element modeling (FEM) method in their study to evaluate the effect of sample dimensions on the tensile curves resulting from coarse-grained micro-copper specimens.

In contrast, Min and Park [69] developed an in-situ SEM system to analyze the properties of thin copper films in real time with a displacement resolution of 5.57 nm and a load accuracy of ±0.015 N. Ando et al. [70] performed microscopic tensile testing on microspecimens of F82H steel with studied cracks to evaluate helium damage. In a medical study, S. M. Lessner et al. [71] used the Miniature single edge notched tensile (MSENT) method and uniaxial tension; the quantitative and qualitative fracture method of atherosclerotic plaque tissue was determined using samples excised from the lining of the carotid artery. Frazer et al. [72] performed micro-tensile testing of AA6061 aluminum alloy samples using plasma-focused ion beam (PFIB) to evaluate their behavior and strength. In the biological aspect, Moon et al. [73] implemented a 3D nano-tensile testing system for a soft mouse lung tissue sample using a 3D printed holder (Figures 3 and 4). Nagai et al. [74] developed a biaxial tensile testing device to accurately measure the mechanical behavior of cross-shaped single-crystalline silicon (SCS) membrane under biaxial as well as uniaxial stresses. The device consists of a piezoelectric actuator, a Linear Variable Differential Transformer (LVDT), a load transducer, and a mechanical actuator with displacement multiplier structures (Figure 5). To demonstrate the potential of the testing technique, the developed Raman spectroscopy was used.

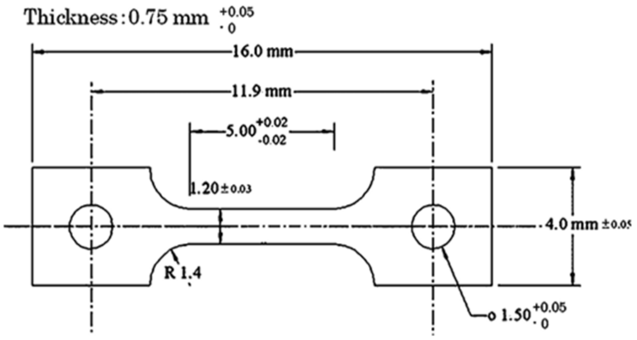

Figure 2. Miniature dog-bone specimen type SS-J3 [66]

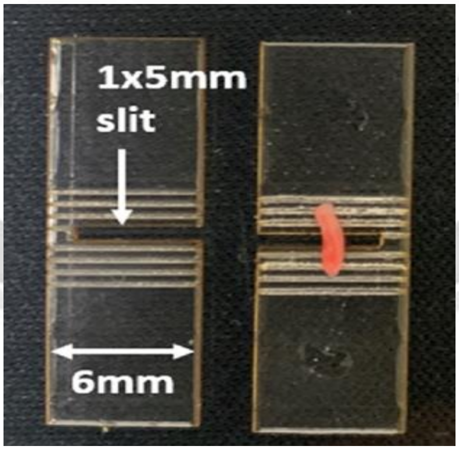

Figure 3. An acrylic specimen mounting base on which a mouse lung slice is placed [73]

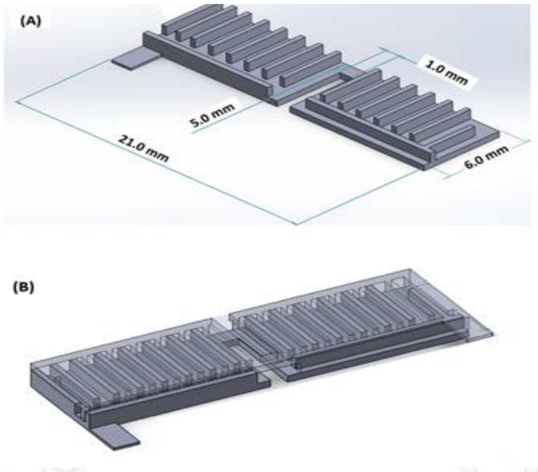

Figure 4. 3D-printed sample holder design: (a) dimensions, (b) final assembly [73]

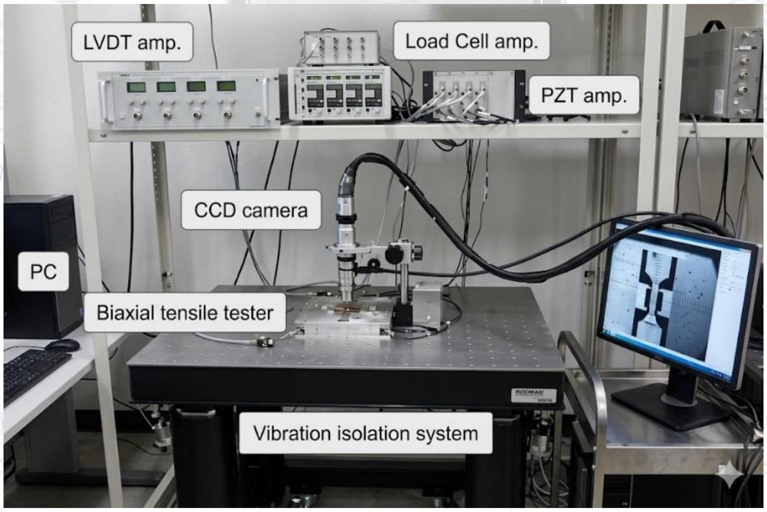

Figure 5. Biaxial tensile testing system for thin films [74]

3.2 Micro-Compression Testing Techniques

Conventional compression tests on metallic materials are typically performed on samples with a diameter of 1 cm or larger, according to ASTM E9 standard. However, reducing the specimen size to 1 mm or less increases the complexity of specimen geometry and alignment [75]. Micro-compression testing has become a popular and essential tool for characterizing the mechanical properties of materials at the micrometer and submicrometer levels, especially for nanowires, thin metal rods, biological tissues, nanoalloys, and ceramics, etc. [76][77][78][79][80][81][82].Many advanced techniques enable testing of microscopic materials that are hard to measure with conventional compression testing equipment due to their micro size. Among these methods, Nazarian et al. [83] presented the incremental compression technique using image-guided failure assessment (IGFA) in conjunction with micro-computed tomography (CT) to analyze the structural failure mechanism of foams and solid biological tissues. Their method enables the observation of three-dimensional microcrack propagation under increased mechanical load in materials such as aluminum foam and silicon carbide (Figure 6). Jural et al.[84] compared the behavior of large and small unconfined compression using a field-based scanning electron microscope (FIB-SEM) on Woodford Shale samples (Figure7), using macropillars and micropillars to explore how size affects fracture response and pore behavior. A. Prasitthipayong et al.[85] performed micro compression testing to evaluate the effect of sample size and radiation exposure on the mechanical performance of 800H steel. The test was conducted at room temperature and elevated temperatures at 300°C, revealing the effects of radiation on strain and deformation mechanisms. In another study, R. M. Gentner et al.[86] performed compression tests on micropillars of ferritic HSLA steel using ECCI and EBSD imaging. The fabrication methodology involved micro-milling micro-cylindrical columns and applying localized compressive loads. The results revealed a relationship between cooling rate, grain size, and dislocation density, providing deeper insights into the microstructural hardening. D. Oji et al. [87] also performed micro-compression tests in parallel with acoustic emission (AE) measurements. They used a simultaneous analysis combining stress and displacement tracking, electron microscopy, and acoustic emission to study the deformation behavior of ion-irradiated zinc microsubstrates (Figure 8). This test method highlighted the emergence of radiation-induced crystalline defects and dislocation behavior, which are responsible for the development of plastic deformation mechanisms in metals with a dense hexagonal core (HCP) structure. Geng et al. [88] advanced this field by combining nanocavity technology with micropillar compression to characterize low-activation ferritic/martensitic (RAFM) F82H steel. The objective is to assess the effects of radiation on the mechanical properties of the material. Using micropillars of diameters ranging from 1 to 8 μm, and performing compression and flexural tests, the researchers successfully characterized the mechanical properties of both irradiated and non-irradiated samples. These techniques emphasize the importance of precision machining (using FIB), ensuring alignment, and microscopic force/displacement control, especially when dealing with materials affected by radiation or with complex hierarchical structures.

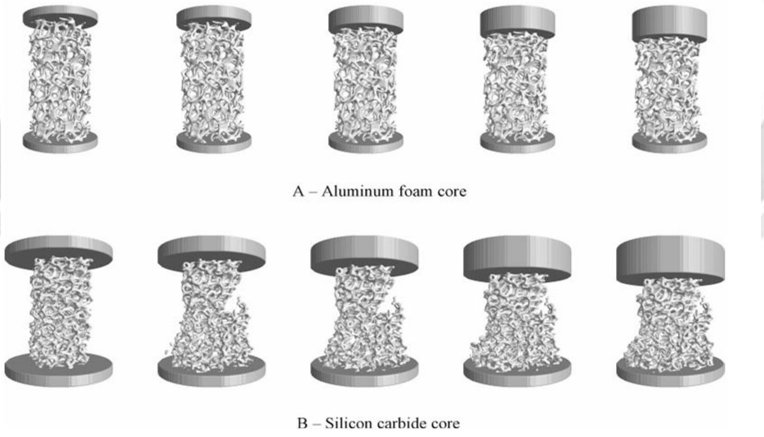

Figure 6. Image-guided failure analysis of representative (A) aluminum (AL-08) and (B) silicon carbide (SiC) [83]

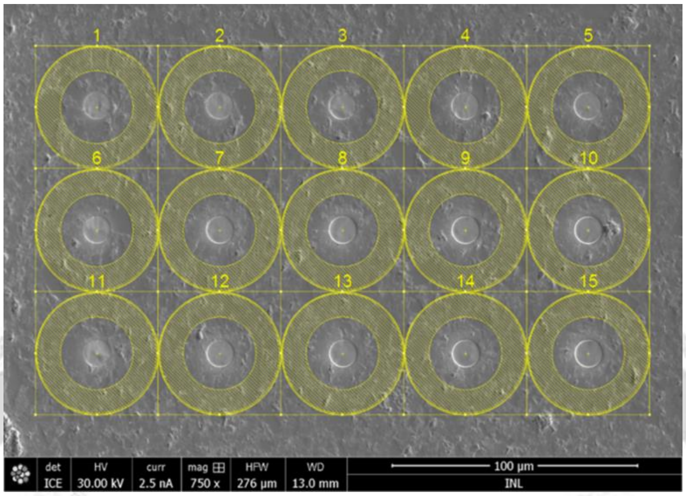

Figure 7. The design and microfabrication of shale columns using FIB.[84]

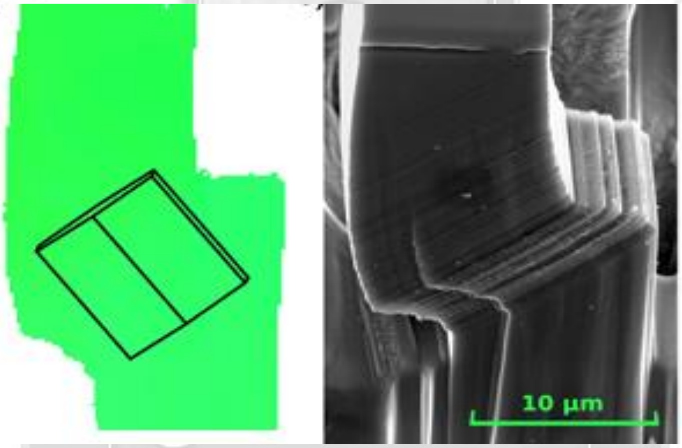

Figure 8: SEM image of a compressed Zn micropillar, with an inset EBSD map showing the crystalline slip direction [87]

3.3. Micro-Bending Testing Techniques

Material samples are often subjected to a variety of mechanical bending stresses, which require measuring their flexural stiffness, modulus of elasticity, and their behavior under bending conditions [89]. With recent innovations in materials engineering and microtechnology, micro-bending techniques have become a primary means of testing micromaterials that cannot be measured using conventional methods. N. C. Reid et al. [90]developed a sophisticated three-point bending device specifically for testing small, 3-mm-diameter discs made of novel materials that are candidates for radiological applications. This device enables accurate assessment of bending and shear stresses. Hofnagels et al.[91]designed a compact, pure bending device that enables bending tests under SEM and OM observation on very small silicon wafers, 200 µm thick, 2 mm wide, and about 4.9 mm long. This device allowed monitoring of brittle fracture and layer peeling with a high loading resolution of only 0.72 mN. Figure 9 illustrates this by displaying a SEM bending test. C. Albert et al. [92] used the three-point bending technique on small cortical bone fragments of sizes not more than 5 mm long by applying loads ranging from 0.05 to 2.0 N with an accuracy of less than 0.01%. This technique enabled the measurement of the bone's Young's modulus and yield stress. Y. Lio et al.[93] studied the effect of grain size and grain boundaries in Fe-6.5 wt% iron-silicon alloys on ductile to brittle transition behavior. Using three-point microbending tests, the results showed that the degree of brittle transformation increases with increasing grain size. J.-H. Choi et al. [94] relied on microcantilever tests to study the bending behavior of polycrystalline copper. Microcantilever arms with thicknesses ranging from 1.6 to 8.6 µm were fabricated from 250 µm-thick copper sheets, with loads ranging from 3.6 µN to 326 µN. A. Bakaev et al.[95] developed a protocol based on three-point micro-bending tests to determine the tensile plastic properties of metals, such as yield stress and stiffness rate. This was achieved by correlating the stress-strain response in three-point bending tests with tensile properties using finite element method (FEM) simulation, and developing a reverse procedure to accurately extract these properties. This approach was validated first on non-radioactive materials and then on radioactive materials, such as neutron-irradiated tungsten. Furthermore, its applicability during the ductility-to-brittle transition (DBTT) was investigated. N. llie [96] focused on studying the effect of surface finishes on dental polymer composites using three-point bending tests, followed by quantitative and qualitative fracture analysis. The results showed that volumetric defects were the primary factor in fracture, while the effect of surface roughness was limited. M. Y. Tasi et al.[97] used the ring-on-ring (RoR) technique to characterize the biaxial bending strength of ultrathin silicon wafers of dimensions 10×10 mm, with thicknesses ranging from 57 to 297 µm. The study relied on theoretical, experimental, and numerical methods, taking into account geometric nonlinearity and material variation.

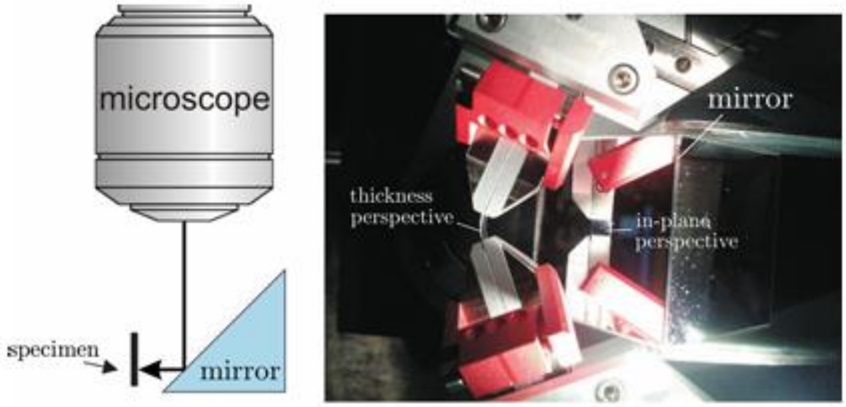

Figure 9. shows the scanning electron **microscope bending test[91].**

Based on the previous presentation of the different techniques, Table (1) summarizes a comprehensive analytical comparison between the tensile, compression and bending techniques, based on documented microscopic and nanoscopic studies of material behavior.

Table 1.Comparative Analysis of Miniature Mechanical Testing Techniques

	Tensile test	Comparison test	Bending test
Geometry	The dog bone, fine wires, thin films [69], and soft tissues [73].	The micro-columns [76],[79], and the miniature cubic specimens [84].	Micro-cantilevers [94], and micro-discs [90], [97].
Stress state	Uniform stress	Uniform stress with a frictional challenge at the base [82].	Stepped stress, maximum stress at the surface [96].
Testing techniques	Digital image correlation (DIC) [66], and tensile tests within an SEM microscope [69].	Scanning electron microscopy (SEM) [79], and Nanoindentation [88].	Miniature three-point bending devices [90] , and contactless testing techniques [91].
Challenges	Difficulty in alignment and gripping of soft tissue samples [73].	Friction at the base of the column and accumulation of crystalline disturbances [78].	The results were affected by the concentration of surface stresses and surface roughness [96] .

4. Standards in Micro-Testing

To perform a mechanical test on a microsample, standards must be followed to ensure the accuracy and reliability of the results. Technical standards are essentially non-mandatory documents. However, compliance with technical requirements, such as specifications, catalogs, data sheets, etc., is mandatory between the manufacturer and the distributor or seller within the scope of the warranty, provided that these requirements are based on regulatory [98]. With the recent advances in mechanical testing techniques, it is necessary to modify traditional standards or develop new standards to suit these tests.

4.1 Sample Design According to Established Standards

Specimen geometry and minimum sample size are the main requirements in most MTTs. The most important standards delineating appropriate specimen designs are those of the American Society for Testing and Materials (ASTM). Other significant standards are the Japanese Industrial Standards (JIS), Chinese National Standards (GB), German Standards Institute (DIN), British Standards (BS), and International Organization for Standardization (ISO). Among these standards, only ASTM is tasked with determining subsamples.

The standards recommend geometry for all specimens, whether they are proportional or disproportionate. Proportional specimens have similar shapes in terms of length to section aspect ratio Lo/Ao or Lo/Do where Lo is original gauge length, Ao is original area of cross section, do is original diameter (mm). A representative design of a tensile sample is shown in Figure 10. L.

Bergonzi et al. noted that generally accepted specimens should be geometrically similar to compare their elongation measurements when they are of different sizes [99].

Conducting tests on microspecimens, such as microwires, thin films, and micropillars, the mechanical behavior may differ significantly from typical bulk material behavior due to size effects, surface behavior, and technical instrumentation limitations. To systematically analyze these differences, researchers compare the results of microsamples to corresponding standard results according to ASTM or ISO standards [100]. For example, studies have shown that the compressive strength of micro-copper columns is significantly higher than that of bulk copper, supporting the "smaller is stronger" phenomenon. Other research on single-crystal gold columns has found a sharp increase in ductile stress as they are reduced in size, a behavior that would not have been observed without comparisons to the behavior of gold in its conventional form.

These comparisons with standard samples are essential for the following considerations:

- Ensuring the calibration of force and displacement sensors in testing systems for micro-materials.
- Distinguishing between the true response of the material and the effects of miniaturization.
- Developing mechanical models that reflect size effects, such as models based on gradient plasticity.

Therefore, integrating data from standard samples is a crucial step for reliable analysis and evaluating the behavior of micro- and nano-materials with high scientific accuracy. Figure 10 shows the standard tensile dog-bone shape sample for round or flat samples, where L1 refers to the gauge length, which is the section whose sides are often parallel or slightly tapered toward the center. L_t represents the total length of the specimen, and R denotes the radius of the transition zone connecting the measuring and clamping areas. For cylindrical specimens, D refers to the diameter, while W refers to the width for flat specimens[99] .

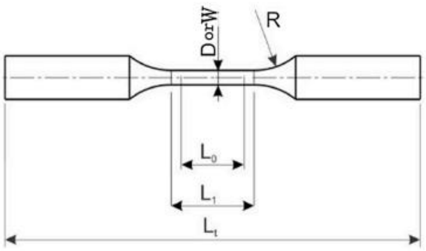

Figure 10. Typical tensile specimen for various metallic and polymeric materials: dog bone type for round specimen or flat specimen [99].

Although overall compression standards, such as ASTM E9 [101], are typically used for metals, alternative standards are available for non-metallic or brittle materials. ASTM C14`24 [102] is for advanced ceramics, while ASTM D695[103] and ISO 604 apply to rigid plastics, and DIN 50106[104] is used in European practice. These standards specify specimen design, alignment requirements, loading rates, and basic data analysis methods for accurately determining compressive strength, yield strength, and Young's modulus across a variety of materials and test conditions. Three- and four-point bending tests are used to determine the mechanical behavior of materials and evaluate their resistance to bending. These tests yield a material's fracture behavior [105], flexural modulus, and flexural strength [106]. Tests are based on standardized criteria to ensure accuracy and reliability, such as ASTM D790 [107] and ISO 178 [108] for plastics, ASTM C1161 [109] for ceramics, and ASTM E290 [110] for metals.

In three-point bending, the maximum stress of the specimen is calculated using the following equation [111]:

$$\sigma = \frac{3FL}{2bd^2} \qquad (5)$$

Where L is the specimen span, b is the specimen width, d is the specimen thickness.

For a four-point bend, where the load is distributed between two internal load points[112], Equation 4 becomes:

$$\sigma = \frac{3F(L-l)}{4bd^2} \qquad (6)$$

Where l is the span between the two internal load points.

However, moving towards the micro- and nano-bending ranges, the accuracy of these equations decreases due to size effects, increased sensitivity to surface defects, and the challenges of accurate measurement. Therefore, researchers rely on more advanced testing techniques [113]or true stress models, along with calibration using standard specimens, to ensure the accuracy and reliability of results.

4.2 Sample Design for Non-Standard Specimens

With the continuous development of microfabrication methods and the use of thin and microscopic materials, it has become difficult to adhere to the standard dimensions recommended by ASTM or ISO standards for tensile, compression, and flexural testing. Special (non-standard) specimens are often designed to meet engineering constraints and precise measurement environments. This is due to the small size of the materials, which may be in the form of micrometer-sized films or wires, making it impossible to prepare samples with standard dimensions [114]

In addition to the miniaturized nature of the devices used in tests, which limits the length of the sample or the installation space [115], there is a need to test materials in their actual state. For example, in silicon wafers or polymer films, reconstituting them according to standard parameters is important to avoid changes in their structural properties [116].

4.2.1 Design of micro-tensile test specimens

In microtensile tests, thin strips or wire specimens with a polished surface are typically used to reduce stress concentration. C. Seguineau et al. [117] performed tensile tests on electrodeposited copper films mounted on a polymer substrate using a custom microplate. The samples were very thin (a few micrometers) and treated to reduce stress concentration and obtain accurate measurements.

In studies of thin films and polymers such as Polydimethylsiloxane (PDMS), samples are often prepared as small strips of approximately 1 mm wide or less and typically 5–10 mm long to ensure easy placement within micro-test platforms, as shown in Figure 11. Some studies used miniature dog bone-shaped samples with an actual length of only 6.6 mm, demonstrating the difficulty of using standard dimensions for micrometric and thin materials [118]. Because PDMS is a flexible material capable of withstanding large stresses, the true stress–strain relationships were used:

$$\sigma * = \sigma_E(1 + \varepsilon_E) \quad (7)$$

$$\varepsilon * = ln(1 + \varepsilon_E) \quad (8)$$

Where $\sigma*$ and $\varepsilon*$ are the true stress and true strain respectively.

Young's modulus can be calculated using Hooke's law:

$$E = \frac{\sigma^*}{\varepsilon^*} \qquad (9)$$

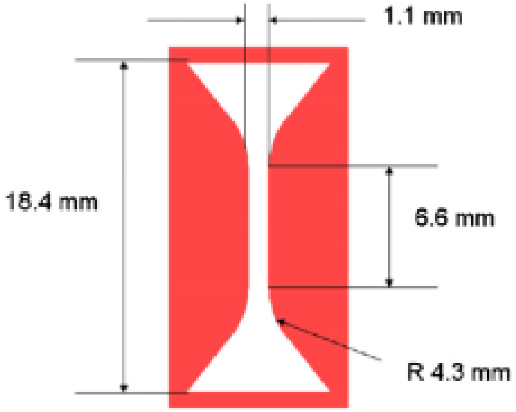

Figure 11. Tensile specimen shape (highlighted in white) and size [118]

4.2.2 Design of micro-compression test specimens

In contrast, micro compression testing requires relatively short and thick specimens to avoid buckling during loading. Therefore, micro piles, or small blocks with a flat surface, are usually prepared. For example, in studies dedicated to testing micro metals, columns of silicon or metal are manufactured with a diameter of 10 to 50 micrometers and a height not exceeding 3 to 5 times the diameter[119] .Polymers can be tested as ultra-thin cubes inside micro-holders, as used in compression systems inside a scanning electron microscope [120]

4.2.3 Design of Bending Test Specimens

Microflexural testing is one of the most important techniques used to evaluate the mechanical properties of thin and brittle materials such as nano-membranes, micro-polymers, and brittle materials such as silicon and glass. These tests minimize clamping effects that can affect the accuracy of measurements, and require small, non-standard samples that comply with the microscopic limitations of the test platforms.

The three-point bending test is one of the most widely used methods for measuring the flexural strength and elastic modulus of small and fine materials. In such tests, the specimen is mounted on two supports, and a single central load is applied, generating tension on the lower surface and compression on the upper surface [121]. Moving towards fine and fragile materials such as thin films, cortical bone, or flexible polymers, it becomes difficult to adhere to standard dimensions (e.g., length ≥ 40–60 mm and width ≥ 10 mm according to ASTM D790). Therefore, miniature and non-standard samples are adopted to fit the engineering constraints of precision instruments. C. Albert et al. designed a very short sample design by using cortical bone specimens of 5 mm long instead of standard lengths, and mounted them on a custom three-point platform within the microbending stage [92][122].

In micrometal testing studies, micropillars are made of silicon or metals with diameters typically ranging from 10 to 50 micrometers, and their heights are no more than 3 to 5 times their diameter. This design takes into account the limitations of instrumentation, such as the precise pressure systems within electron microscopes. For example, Patel and Srinivasn studied metal rods (nickel foils) with thicknesses of 15, 25, and 50 µm that were bent using a non-standard microbending technique, with a large length-to-diameter ratio (L/H) and a non-standard clamping method [122].

Four-point bending test is an improvement on the three-point test and is used to reduce stress concentration at a single point, allowing for a more uniform stress distribution in the center of the specimen, and is more accurate for brittle materials. Mead et al. [123] used microbridge specimens made of Al–SiN–GaAs layers with micrometric dimensions (less than 1 mm in length) to test peeling and bending behavior using four-point microbending with loads less than 1 mN. In some studies, on metal or polymer films, flexible silicone or polymer samples of 10-15 µm in length were used to fit into microscope holders placed inside an electron microscope or nano system.

4.3 Specimen Preparation and Handling Issues

Preparing samples for micromechanical tests—such as tensile, compression, and bending, is a fundamental challenge, as the small dimensions of samples (micrometric or nanoscale) make them more sensitive to surface deformations, residual stresses, and clamping conditions. The most important challenges facing researchers in this field can be summarized as follows:

a) **Mechanical accuracy in cutting samples:** At the micrometer level, any deviation in the specimen dimensions leads to a significant difference in stress concentration and measurement results. An example of this is the use of technology to cut extremely thin slices, such as silicon wafers that are one micrometer thick, less than 1 mm wide, and of a length suitable for carrying electron microscopes or nano-drills. This is typically done using lithography or laser cutting [124].

b) **Residual stresses and surface treatment:** During the preparation of thin films or microstructured substrates, residual stresses are generated as a result of manufacturing processes such as chemical deposition or ion etching. These stresses can significantly alter the mechanical response. For example, Wu Tang et al. demonstrated that using low-temperature treatment (>200°C) reduces internal stresses. This improvement contributes to preventing deformation during clamping and reducing sudden fracture during micromechanical testing [125].

c) **Installation and border control:** In microtensile or microflexural tests, incorrect specimen mounting leads to lateral sliding or twisting, altering the stress distribution [126].

d) **Dealing with the fragility of fine materials:** Delicate materials, such as ceramic membranes or soft polymers, can be damaged during handling if special precision tools are not used. Therefore, they are prepared directly on the substrates used in the test to reduce the transport stages[97].

5. Advanced Micro- and Nano-Scale Testing Techniques

As a result of the development of micro- and nano-experimental mechanics, advanced testing techniques have emerged to measure the mechanical properties of materials at very micro-scales. Here, conventional techniques have become ineffective. These techniques rely on micro-loading systems that are often combined with scanning electron microscopes (SEM/TEM) or nanomicroscopes, allowing high-resolution monitoring of mechanical response during testing. This allows for high-precision monitoring of mechanical response during testing. The most important of these techniques are:

a) In-situ SEM/TEM testing: microscopic samples (such as nanopillars or thin films) are tested using direct imaging of deformation and fracture, which gives information about failure mechanisms at the microscopic level [127], [128].

b) Nano-indentation: A technology that uses a sharp, nano-sized tip to perform precise bending, compression, and tensile tests, measuring properties such as Young's modulus and hardness with very high accuracy [129].

c) Embedded systems: A small mechanical platform that can be mounted inside a scanning electron microscope or automated atomic energy microscope, allowing three- or four-point bending and compression tests on micropillars, with immediate response monitoring [130].

These advanced methods provide high resolution of force and displacement (μN and nm), and allow understanding of the behavior of materials under real loading conditions at the microscopic level, which contributes to the development of advanced materials such as nano-membranes and micro-composites.

6. Case studies on Micro mechanical Testing

6.1 Case Study 1: Tensile testing of additively manufactured homogeneous and hybrid materials

Anigani Sudarshan Reddy et al. presented a comparative study to evaluate the mechanical properties of alloys manufactured using the Direct Metal Laser Sintering (DMLS) technique, as well as hybrid alloys partially based on conventional materials [131], as shown in Figure 12. To achieve this, the researchers used miniaturized tensile testing as a practical alternative to traditional testing, which requires large quantities of material that may not always be readily available in complex additive manufacturing components.

Micro-tensile strength samples were fabricated with precise dimensions (0.5 mm thickness, 2 mm width, and 6 mm measuring area), and their mechanical response was compared to that of standard tensile strength samples prepared according to ASTM E8/E8M, in order to assess the reliability of the micro tests. The results showed that the mechanical properties obtained from the micro samples, such as yield strength and tensile strength, exhibited high agreement with the results of the standard samples for most of the studied alloys, with differences not exceeding 5%.While some alloys, such as IN718 and Ti6Al4V, exhibited relatively higher variations (around 10%) in their initial state, these variations disappeared after heat treatment, suggesting that the microstructure resulting from the manufacturing process—rather than the sample size—was the cause. Microscopic tensile tests demonstrated a clear ability to assess the integrity of the bonding surfaces in hybrid alloys composed of imprinted and conventional zones. The bonding zones held up, while the softer materials failed .The study concluded that microtensile testing is a practical and effective option for quality control and reducing time and cost in additive manufacturing, with potential applications in the evaluation of hybrid structures and their use in advanced industries such as aerospace and medical devices.

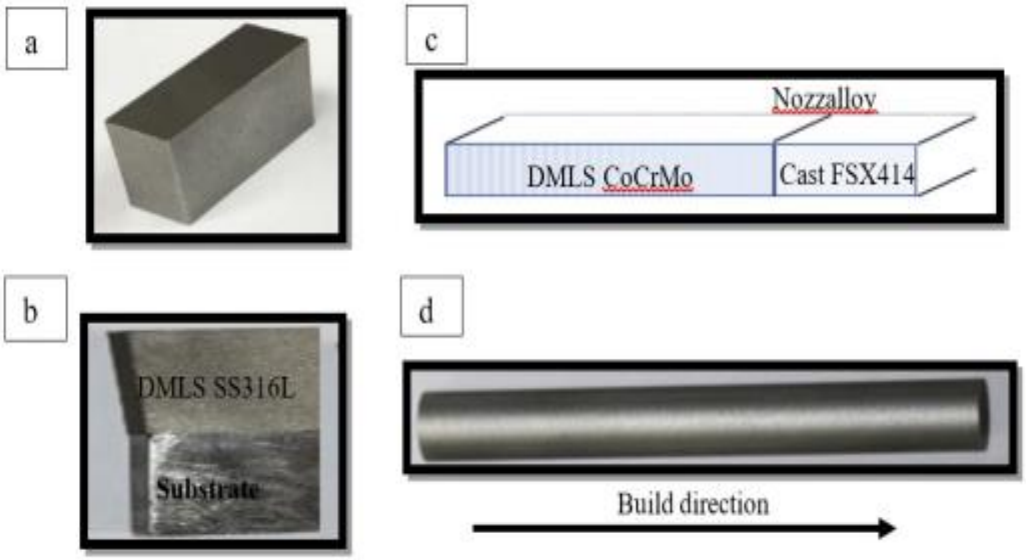

Figure 12. The natural specimens used in micro-scale testing: (a) Homogeneous DMLS specimen, (b) Hybrid specimen –DMLS SS316L on X20Cr13, (c) Hybrid specimen - DMLS CoCrMo welded on FSX414, and (d) Cylindrical DMLS specimen [131].

6.2 Case Study 2: Microflexural Tests to Reveal the Behavior of Surface Structures in Frictional Environments: A Study of Three Representative Cases

In this study, Rainer Hahn et al. [132] focused on a fundamental problem: the difficulty of evaluating the local mechanical properties of near-surface structures formed at the micrometer level, which cannot be tested using conventional methods. The study used three common model cases in frictional systems: (1) a used train wheel, (2) a cylindrical bearing ring, and (3) a laser-treated self-lubricating coating. In each case, focused ion beam etching (FIB) was used to create V-shaped microbeams, which were subsequently put through micro-bending tests using scanning electron microscopy (SEM) Stress-displacement curves were recorded, and crack initiation and propagation were directly observed. According to the first case's results, the brown layer that developed close to the train wheel's surface (brown etching layer (BEL) area) (Figure 13) primarily displayed plastic behavior without crack initiation, demonstrating the layer's capacity to withstand deformation. In the second case, the investigation showed a distinct variation in the bearing's near-surface structure mechanical response (Figure 14). When compared to volumetric or deformed structures, the white etching layer (WEL) region showed higher vulnerability to crack initiation and propagation. In the third case, the study showed that the fracture mechanism and mechanical behavior are directly influenced by the location of cracks within the self-lubricating coating (Figure 15) (in the nickel matrix or in the sulfur-rich phases). The results confirm that this method provides a very accurate analysis of micromechanical behavior, complementing microstructural characterization and hardness testing techniques, it holds promise for understanding the mechanisms of friction, wear, and component failure in tribological systems.

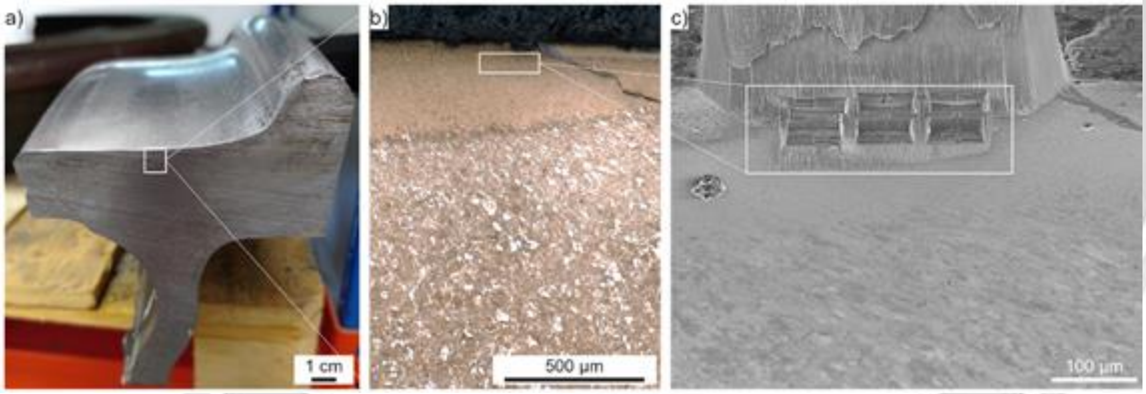

Figure 13. Case 1 shows (a) Used railway wheel, (b) Exposed BEL layer near the crack, (c) Preparation of cantilevers for microbending tests.[132]

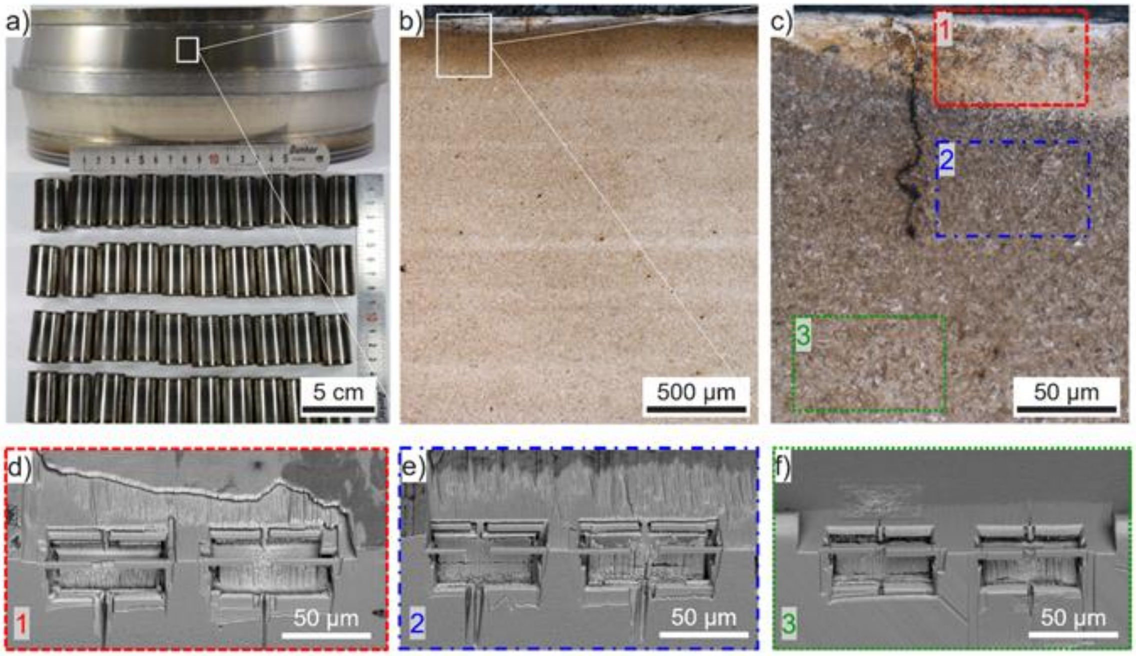

Figure 14. In Case 2 (a) a cylindrical bearing is used in a cold rolling mill, (b) detection of different regions of the microstructure, (c) preparation of suspension arms for tests in the three regions (d,e,f).[132]

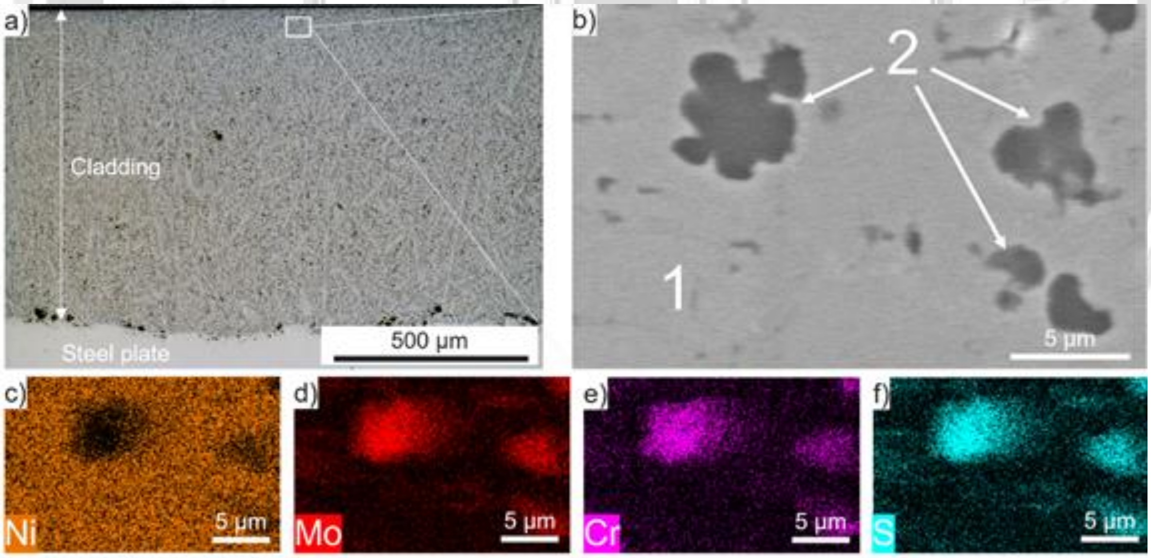

Figure 15. The cross-section of the self-lubricated laser coating (a, b) shows a heterogeneous structure with a bright matrix (1) and random dark particles (2), and EDX analysis reveals nickel in the matrix and particles composed of molybdenum, chromium, and sulfur (c-f).[132]

6.3 Case Study 3: High Strain Rate Tensile Testing of Bicrystalline Silver Nanowires

Rajaprakash Ramachandramoorthy et al.[133] tested bicrystalline silver nanowires using a microelectromechanical testing rig (MEMS) inside a scanning electron microscope (SEM) at strain rates ranging from 2×10^{-4}/s to 2/s. The results demonstrated a mechanical behavior that was highly dependent on the strain rate, with a distinct shift from brittle to plastic failure noted at a critical strain rate of roughly 0.2 s^{-1}. Due to manufacturing-related surface flaws, the plastic deformation was restricted and localized at low strain rates, resulting in failure that resembled brittle behavior. On the other hand, plastic deformation was dispersed along the wire's length at high strain rates, along with strain stiffening and a noticeable increase in ductility. Transmission electron microscopy (TEM) and high-resolution transmission electron microscopy (HRTEM) analysis, which revealed an increase in dislocation density, the spread of plastic deformation zones with increasing strain rates, and grain boundary migration, corroborated these experimental findings. Additionally, molecular dynamics (MD) simulations were carried out, which showed that the strain stiffening and plastic behavior at high strain rates are caused by mechanisms like surface dislocation generation, their interaction with grain boundaries, and the formation of stair-rod dislocations. This study provides an important scientific basis for the design of nanomaterials used in dynamic and advanced applications by showing how high-speed tensile testing at the nanoscale reveals time-dependent deformation and failure mechanisms when combined with atomic simulations and theoretical models.

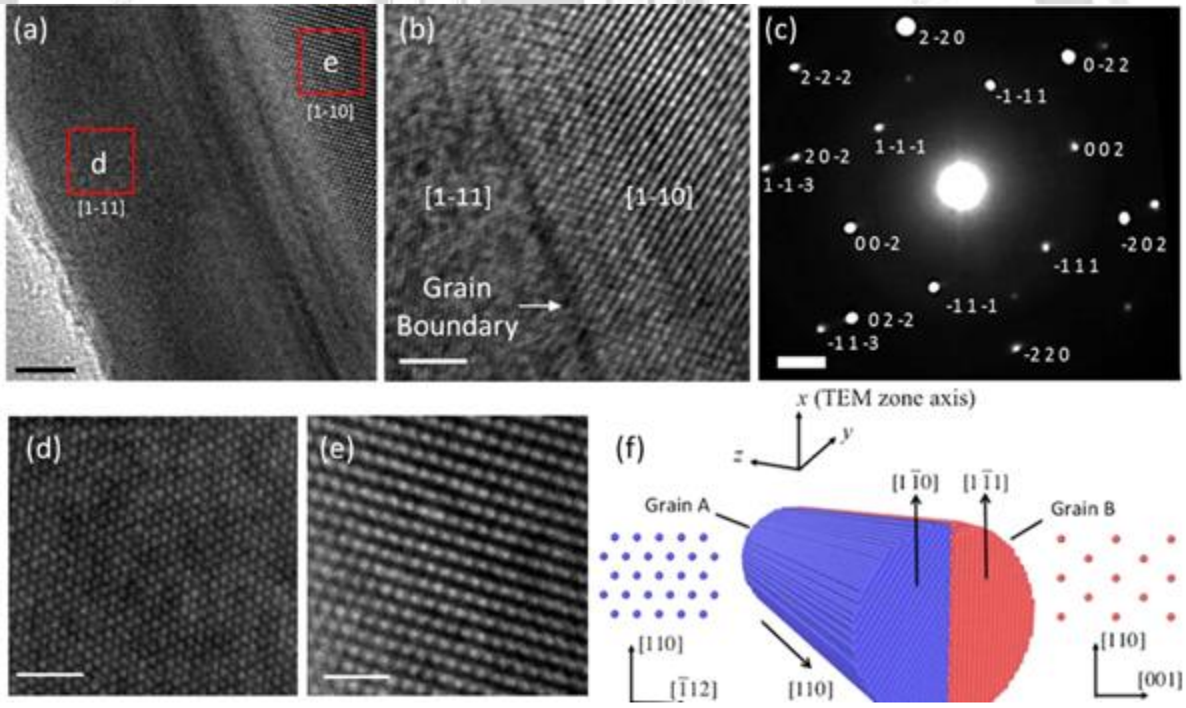

Figure 16. Atomic structure of a bicrystalline silver nanowire: (a) Transmission electron microscope (TEM) image showing the bicrystalline nature, (b) High-resolution transmission electron microscope (HRTEM) showing grain boundaries, (c) SAED diffraction pattern, (d, e) High-resolution TEM images of the two single-crystal domains], and (f) Atomic model used in dynamic simulation.[133]

7. Future Directions and Conclusion

In the coming years, micromaterial testing techniques are likely to evolve significantly with advances in technology. Advanced technologies such as computer modeling and artificial intelligence will continue to improve the ability to interpret the behavior of micromaterials and analyze data with great accuracy. With the development of high-precision manufacturing technologies such as micro machines and 3D printing, it will be possible to produce precise and complex test samples, creating opportunities for new applications in various industries. Also, there will be an urgent need to develop standards for standardized testing techniques to ensure the accuracy of results. The growth in these technologies requires the improvement of higher-precision and higher-performance devices, in addition to overcoming the challenges related to producing micro-samples and ensuring the accuracy of measurements. In conclusion, micro-sample testing has become an important and advanced field in various advanced technological industries such as aerospace, aviation, engineering, and microelectronics. With the continued reduction in the size of components and the increasing demand for studying the mechanical properties of micro-materials, it has become necessary to modify and develop testing methods to suit these new requirements. Despite the remarkable progress in micro-sample testing technology, there are still ongoing difficulties in producing samples with extreme precision and ensuring correct measurements in miniaturized conditions. The trend towards standardizing advanced testing techniques will contribute to the adoption of these methods in various industries and improve their efficiency. Ultimately, micro-sample testing is a pivotal tool for encouraging innovation in the development of small and advanced components, and efforts continue to bridge the current technical gaps to ensure accurate and initial value.

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الاختبارات الميكانيكية للأجزاء المصغرة، والتقنيات والأساليب: مراجعة

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الخلاصة

ازدادت شعبية اختبار المكونات الدقيقة بشكل ملحوظ خلال العشرين عامًا الماضية، ويعود ذلك في معظمه إلى تصغير أحجام الأنظمة والأجهزة. وقد فرض التطور المستمر للتقنيات، مثل الهندسة الطبية والحيوية، وأنظمة الكهروميكانيكية الدقيقة، وقطاع الطيران، ضرورة ملحة لتحسين أساليب الاختبار الميكانيكي للمكونات الصغيرة. تتطلب هذه الصناعات أجزاءً معقدة ودقيقة، مما يستلزم تطوير أساليب الاختبار لتلائم هذه الأحجام الصغيرة. تستعرض هذه الدراسة الأساليب والتقنيات الحالية للاختبار الميكانيكي للمكونات المصغرة، ومدى ملاءمتها للمكونات متناهية الصغر. وقد تم تلخيص أكثر من مئة دراسة في هذا المجال، مع استعراض أحدث التطورات في مجال اختبار المكونات الدقيقة، بالإضافة إلى التركيز على الأساليب والتقنيات المستخدمة. كما تم تسليط الضوء على التحديات المستقبلية ومسارات البحث التي تُسهم في تطوير هذه التقنيات. تُقدم هذه الرؤى إرشادات قيّمة للباحثين والمهندسين والفنيين العاملين في مجال التصنيع الدقيق، مثل أنظمة الكهروميكانيكية الدقيقة (MEMS)، والإلكترونيات، وأشباه الموصلات، وتطوير الأجهزة الطبية الحيوية. يمكن أن يركز التصور المستقبلي على الجمع بين أساليب الاختبار، التدميرية وغير التدميرية، المرتبطة بالنمذجة الحاسوبية.

الكلمات الدالة: الأجزاء الدقيقة، الاختبارات الميكانيكية الدقيقة، الاختبارات الميكانيكية الدقيقة/النانوية في الموقع، توصيف الأحمال والإزاحات على نطاق صغير.