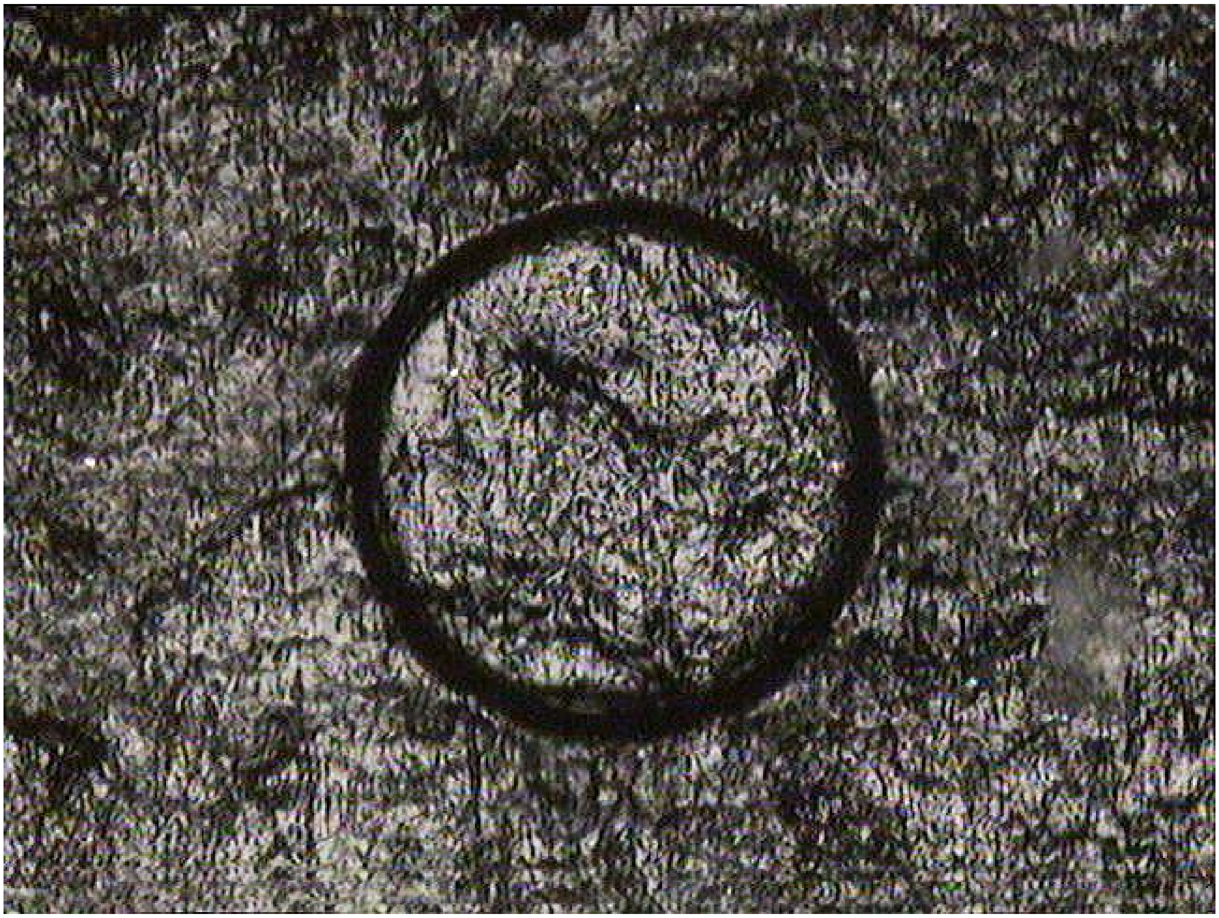
BREAKTHROUGH INDENTATION
YIELD STRENGTH TESTING



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INTRO

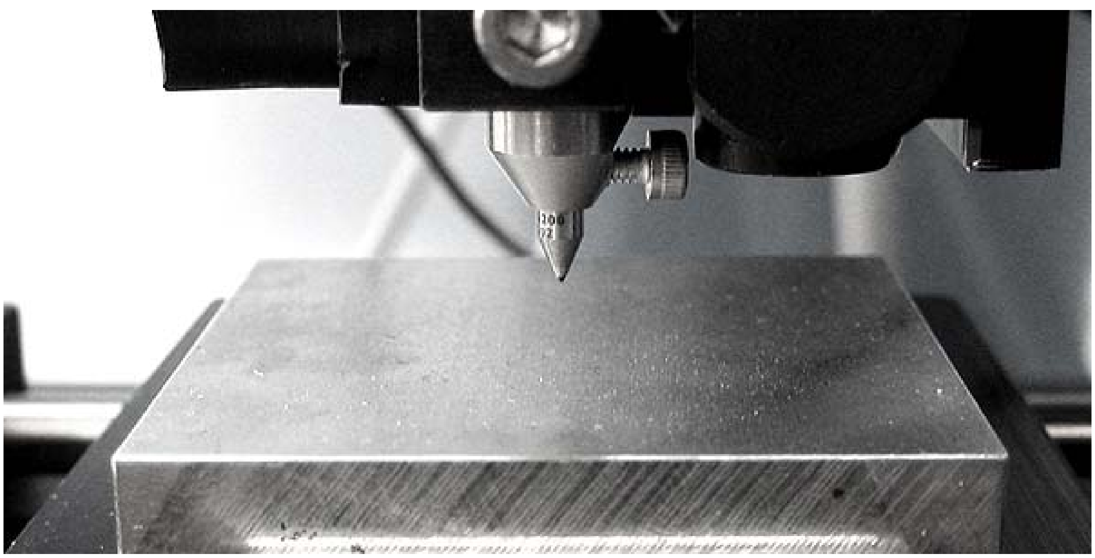
Traditionally yield strength has been tested by using a tensile testing machine, a large instrument requiring enormous strength to pull apart metal, plastic and others. The yield strength (also known as yield point) within materials science is the point of stress that a material starts to deform plastically. Before reaching the yield point a material will deform elastically but returns to its original shape when stress is removed. Therefore, it is critical within engineering to reliably obtain what is ultimately a materials yielding point. Until now the most reliable way took enormous machine effort, sample preparation and or was impossible to perform on small samples or localized areas. Nanovea's patent pending procedure will change the standard for which yield strength testing is performed.

BREAKTHROUGH INDENTATION FOR YIELD STRENGTH TESTING

By using Nanovea's Mechanical Tester in indentation mode, using a cylindrical flat tip, yield strength data can be easily and reliable obtained. For years now, the indentation test has been used for hardness and elastic modulus measurements, among many others. There has traditionally been an issue with linking macro tensile properties to what was measured during an indentation test. Many studies measuring with spherical tips have allowed stress-strain curves but were never able to give reliable tensile yield strength data that corresponded directly to macro tensile data. Nanovea's patent pending method, using a cylindrical flat tip, gives yield strength directly comparable to what is measured by traditional means. It is believed that the load per surface area at which the cylindrical flat tip penetrates, at increased speed, is directly linked to the load versus surface area at which the material starts flowing in a tensile mode test. Therefore, reliable yield strength data on an endless list of materials, small or large has never before been obtainable until now.

MEASUREMENT OBJECTIVE

In this application, the Nanovea Mechanical Tester, in Microindentation mode, is used to study the Yield Strength of various materials for comparative review. The samples were chosen for there commonly recognized Yield Strength values to display the reliability of the indentation method. During the indentation test a cylindrical flat tip with a known area is used to indent while depth versus load is recorded. On the resulting curve, the change from increasing slope to decreasing slope is related to the load at which plastic deformation occurs. This load over area contact gives the yield strength of the material under test.

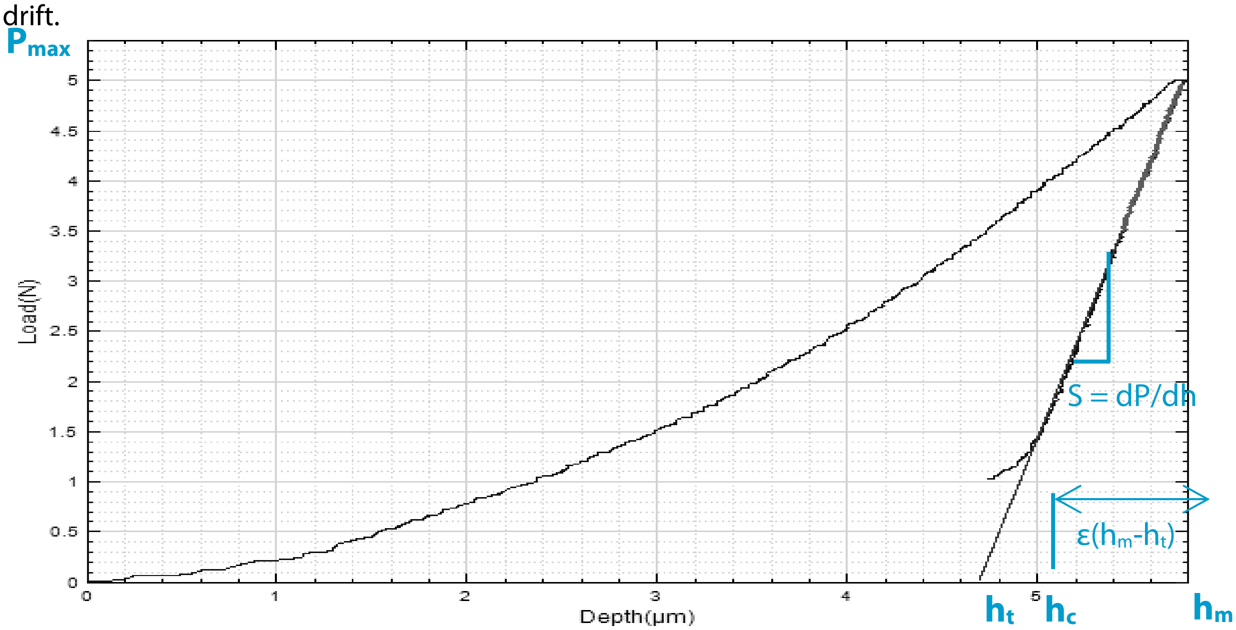


MEASUREMENT PRINCIPAL

The Microindentation test is based on the standards for instrumented indentation, ASTM E2546 and ISO 14577. It uses an established method where an indenter tip with a known geometry is driven into a specific site of the material to be tested, by applying an increasing normal load. When reaching a pre-set maximum value, the normal load is reduced until partial or complete relaxation occurs. This procedure is performed repetitively; at each stage of the experiment the position of the indenter relative to the sample surface is precisely monitored with an optical non-contact depth sensor. For each loading/unloading cycle, the applied load value is plotted with respect to the corresponding position of the indenter. The resulting load/displacement curves provide data specific to the mechanical nature of the material under examination. Established models are used to calculate quantitative hardness and modulus values for such data. The MHT is especially suited to perform tests of penetration depths in the micrometer scale and has the following specifications:

Analysis of Indentation Curve

A typical load/displacement curve is shown below, from which the compliance C = 1/S (which is the inverse of the contact stiffness) and the contact depth h_c are determined after correction for thermal drift.



A simple linear fit through the upper 1/3 of the unloading data intersects the depth axis at h_t. The stiffness, S, is given by the slope of this line. The contact depth, h_c, is then calculated as, where ε depends on the investigated material:

$$h_c = h_m - \varepsilon(h_m - h_t)$$

In practice, a more meticulous approach is used where a power law function is used to describe the upper 80% of the unloading data:

$$P = P_{max}\left(\frac{h - h_O}{h_m - h_O}\right)^m$$

where the constants m and h_O are determined by a least squares fitting procedure. The contact stiffness S (=1/C) is given by the derivative at peak load:

$$S = \left(\frac{dP}{dh}\right)_{max} = mP_{max}\left[\frac{(h_m - h_O)^{m-1}}{(h_m - h_O)^m}\right] = mP_{max}(h_m - h_O)^{-1}$$

and the tangent depth, h_t, is thus given by:

$$h_t = h_m - \frac{P_m}{S}$$

The contact depth, h_c, is then:

$$h_c = h_m - \varepsilon(h_m - h_t)$$

where ε now depends on the power law exponent, m. Such an exponent can be summarized for different indenter geometries:

Elastic Indentation Behavior (indenter geometry)	m (power law exponent)	ε
Flat	1	1
Paraboloid	1.5	0.75
Conical	2	0.72

Young's Modulus

The reduced modulus, E_r, is given by:

$$E_r = \frac{\sqrt{\pi}}{2}\frac{S}{\sqrt{A_c}} = \frac{\sqrt{\pi}}{2}\frac{1}{C}\frac{1}{\sqrt{A_c}}$$

which can be calculated having derived S and A_c from the indentation curve using the area function, A_c being the projected contact area. The Young's modulus, E, can then be obtained from:

$$\frac{1}{E_r} = \frac{1-\nu^2}{E} + \frac{1-\nu_i^2}{E_i}$$

where E_i and $_i$ are the Young's modulus and Poisson coefficient of the indenter and the Poisson coefficient of the tested sample.

Hardness

The hardness is determined from the maximum load, P_{max}, divided by the projected contact area, A_c:

$$H = \frac{P_{max}}{A_c}$$

Additional Tests include:

Creep, Stress-Strain, Fracture Toughness, Plastic & Elastic Energy, Flow Stress, Indentation & Plastic Work, Fatigue, Hardness and elastic modulus vs. depth, Compression and many others.

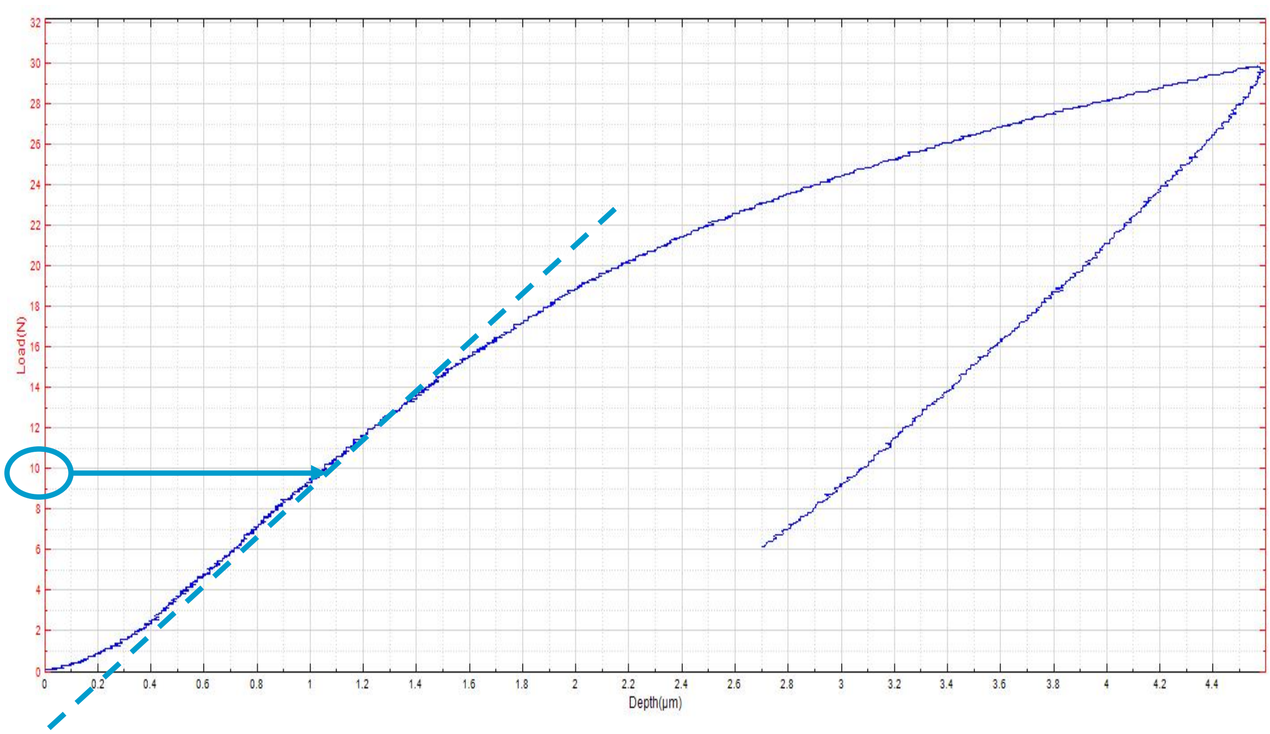
TEST CONDITIONS & PROCEDURES

The following tests were performed on the Nanovea Mechanical Tester in the Microindentation mode. The tip used was a cylindrical flat tip diamond of 200microns diameter. The maximum load was chosen to be well beyond the yield pressure for the material tested. Depth versus load was recorded during the test. The inflection point of the first derivative or a change from positive to negative of the second derivative correspond to the yield point measured. Physically, as the load increases the local roughness is squeezed and the sample is squeeze down as the depth increase from slow to even slower because of the flat surface. When the yield point start the flat tip starts penetrating at increased speed since the supporting load capacity of the material has been passed. We have compared these yield strength measured by this technique with generally accepted values in the literature for a wide range of materials.

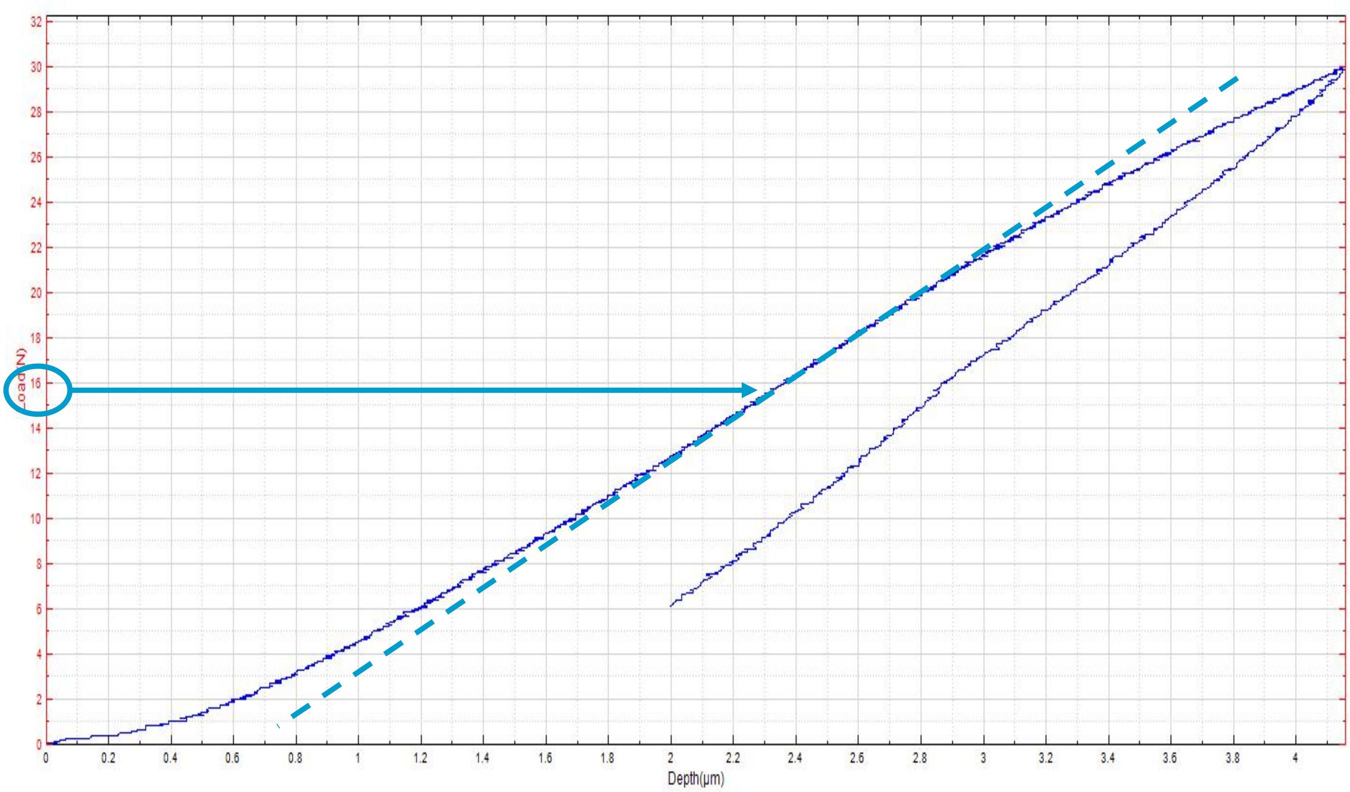
RESULTS

Here we show the comparative results between Indentation produced yield strength results and commonly known parameters of materials tested with traditional tensile testing.

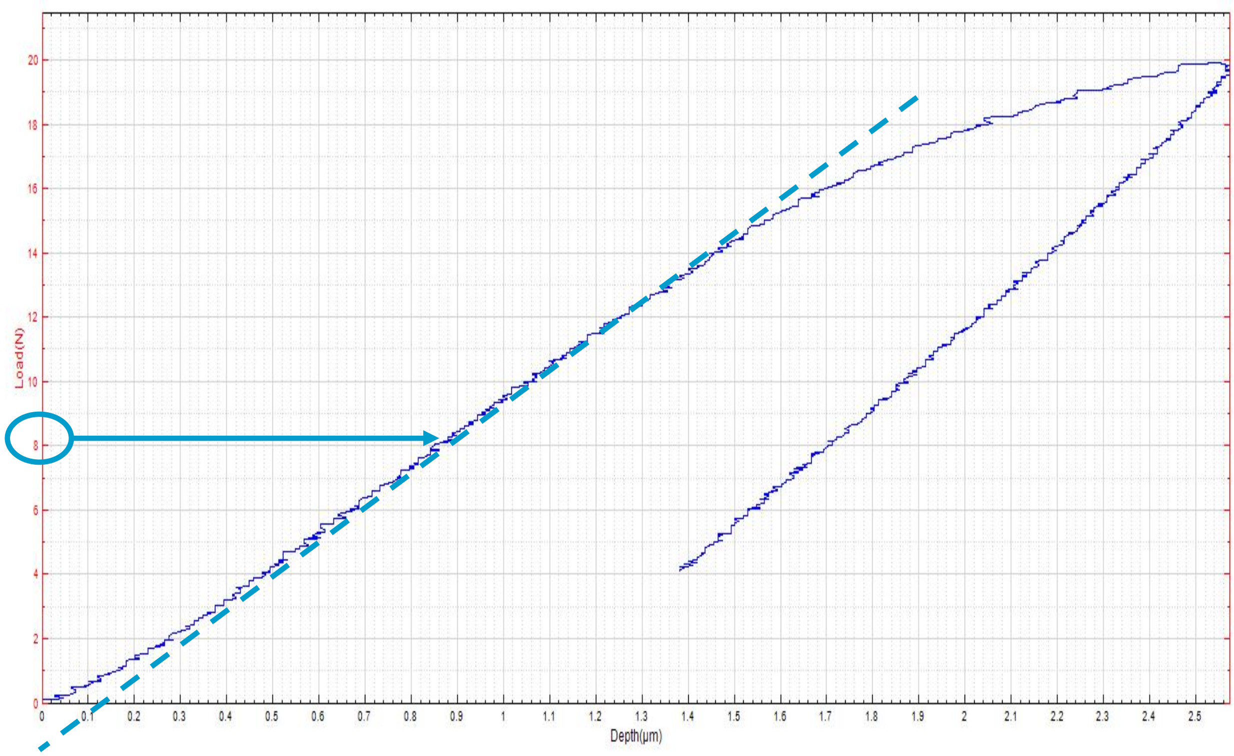
Indentation Method vs. Tensile Method Yield Strength			
Material	**2nd Derivative - Inflection Point N**	**Indentation Method MPa**	**Yield Strength Literature MPa**
Aluminum 6061	10	318	
	9.4	299	
	9.7+/- 0.35	309+/-11	**309**



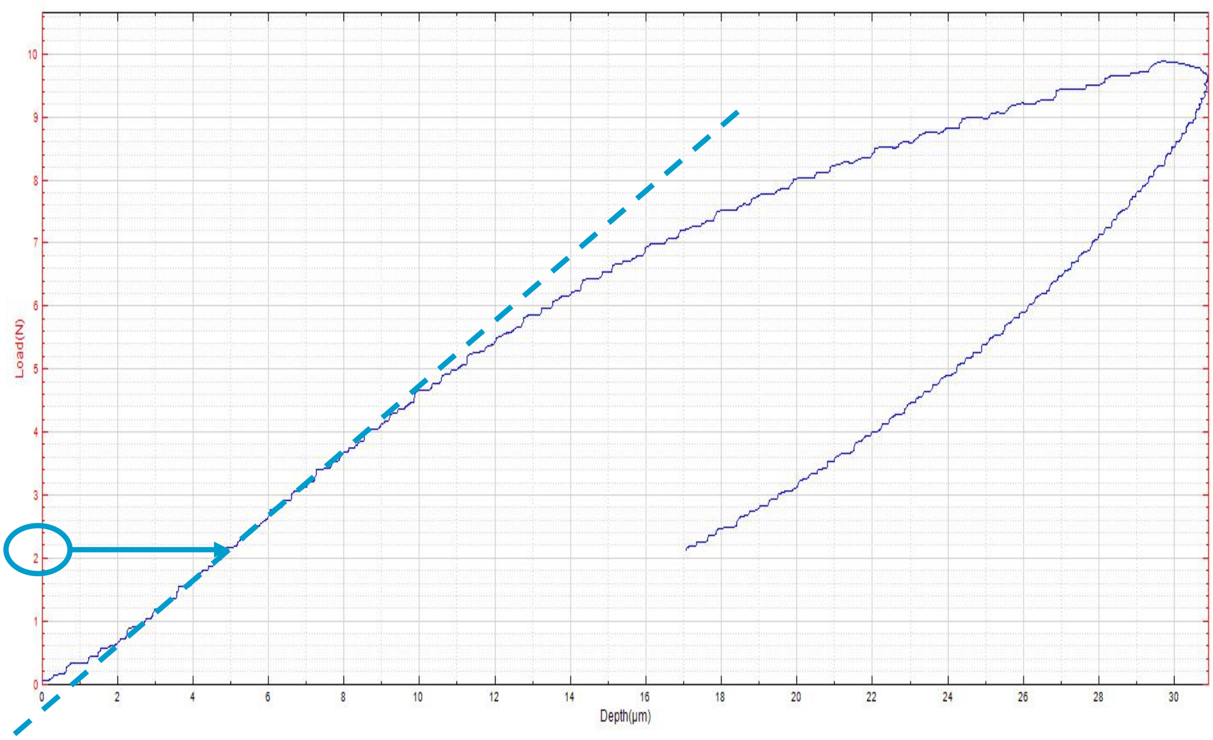
Indentation Method vs. Tensile Method Yield Strength			
Material Aluminum 7075	**2nd Derivative - Inflection Point N**	**Indentation Method MPa**	**Yield Strength Literature MPa**
	16.8	535	
	16.6	528	
	17.8	566	
	17.07+/- 0.45	543+/-14	**550**



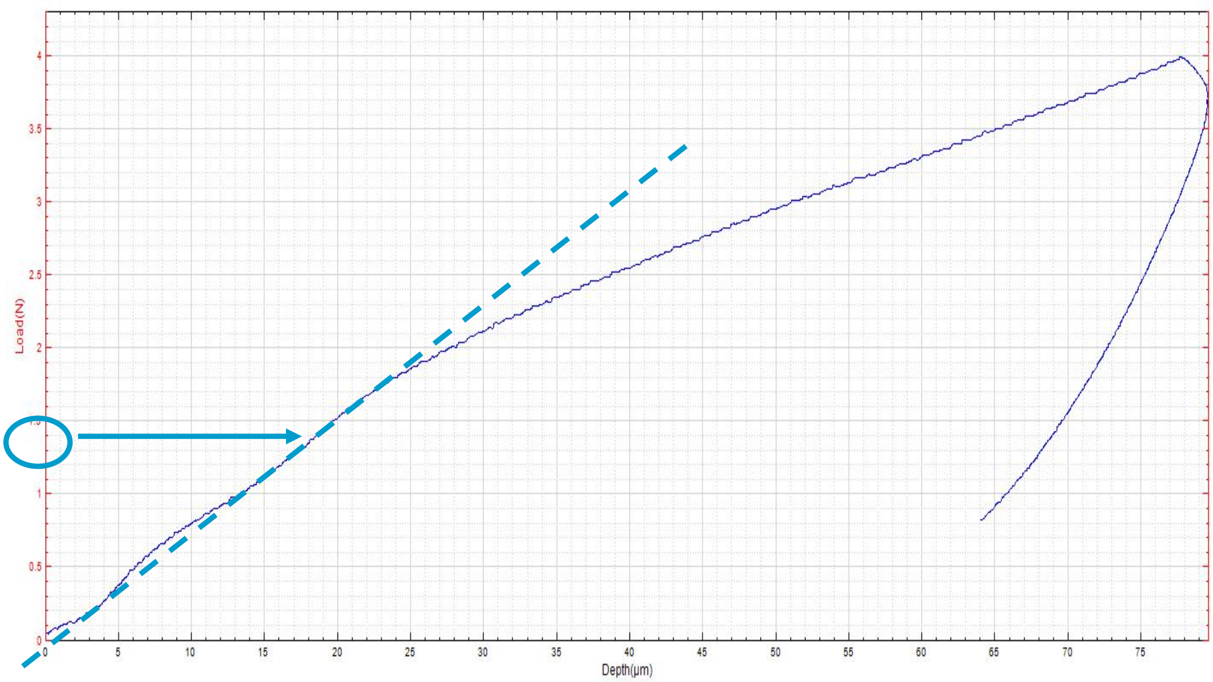
Indentation Method vs. Tensile Method Yield Strength			
Material Copper C10200 Oxygen Free	**2nd Derivative - Inflection Point N**	**Indentation Method MPa**	**Yield Strength Literature MPa**
	8	255	
	8.5	271	
	8.25+/- 0.25	263+/-8	**245-315**



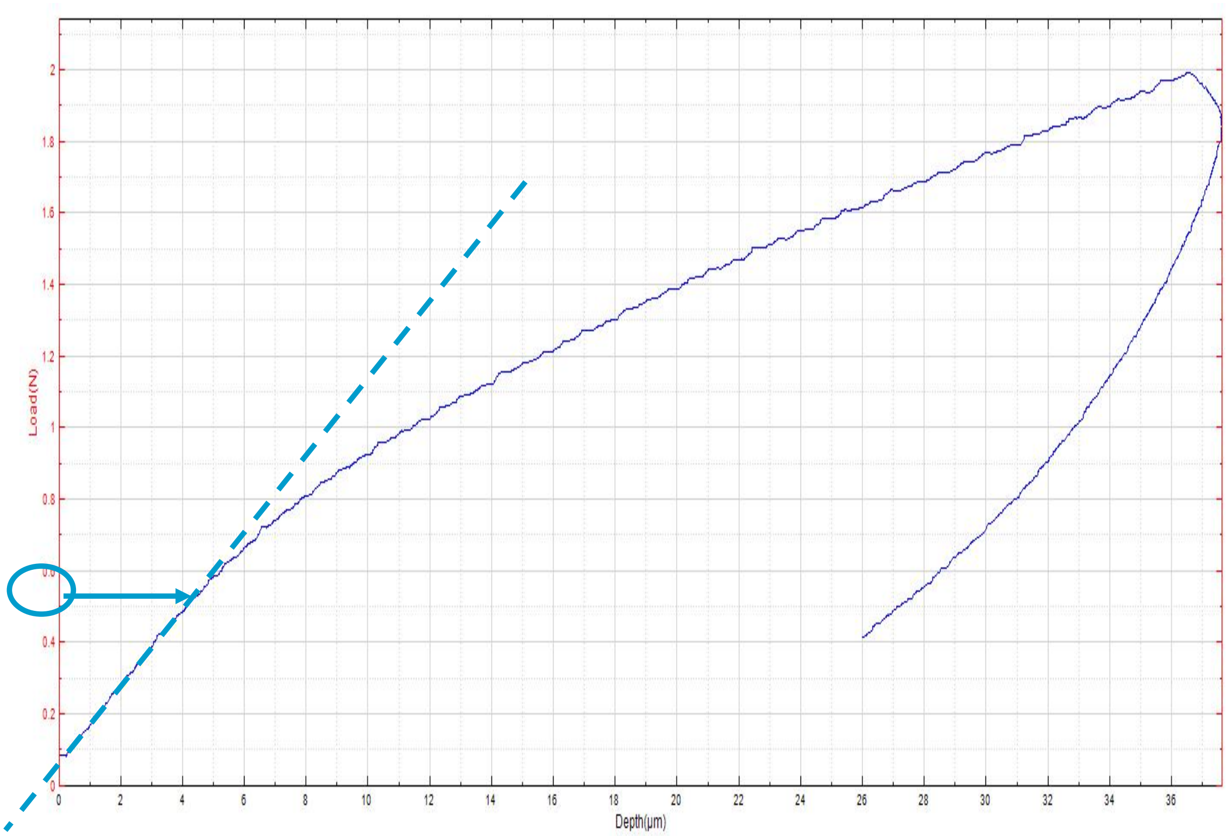
Indentation Method vs. Tensile Method Yield Strength			
Material Delrin	**2nd Derivative - Inflection Point N**	**Indentation Method MPa**	**Yield Strength Literature MPa**
	2.11	67.2	
	2.25	71.6	
	2.18+/-0.06	70.3+/-1.9	**66-73**



Indentation Method vs. Tensile Method Yield Strength			
Material Pine Wood	**2nd Derivative - Inflection Point N**	**Indentation Method MPa**	**Yield Strength Literature MPa**
	1.35	43.0	
	1.45	46.2	
	1.40+/-0.05	44.5+/-3.6	**40**



Indentation Method vs. Tensile Method Yield Strength			
Material Teflon	**2nd Derivative - Inflection Point N**	**Indentation Method MPa**	**Yield Strength Literature MPa**
	0.528	16.8	
	0.46	14.6	
	0.499	15.9	
	0.50+/-0.03	16+/-1	**15**



DISCUSSION

It is true that the relationship between micro hardness and yield strength has been well established for some materials. This is especially true for Steel. However, previous technique needed long studies to create these relations between micro hardness and yield strength. This new technique can directly measure yield strength with one measurement that takes less than 1minute and can be performed on area as small as 5microns with parts in the micron range. The value is also directly calculable as the yield strength with no guessing. Some areas of work such as microelectronics, solar and medical devices have long looked for ways to measure yield strength on small material parts. Others have wanted to measure this on coatings or films. There is no existing reliable relation that exists for this until now.

In regards to bulk testing, it is true that this new technique will provide a higher value than what will be found by tensile test if there are macro defects. However, this optimum value without counting the defects can give good insights on where the issue of the product can be. Is it the composition or is it weak points that are the source of failures? We have tested a pine wood piece which represents this well. The value we obtained was somewhat higher than what was reported in literature. I assume that the macro failure comes at lower forces from knots and defects found inside the wood. You would then obtain a different value on the macro scale for each piece of wood that you would test. We would obtain a much more reproducible value of the intrinsic yield strength of the material. There will still be a use for tensile testing to check production of parts and introduction of dislocations/cracks, voids or other defects. However, having a way to determine the true yield strength of the material composition will prove to be indispensable.

From the measurements that we have made on various materials in our Application Note, we have obtained directly without any mathematical corrections and obtained values that correlate directly with tensile yield strength published for these materials. In our test, the flat area is only 200micron. If there are features at a larger scale, it will not be taken in account in the failure point. Actual, yield point by tensile test will "always" give less than the ideal material yield strength because it contains various points, line and macro defect. It should be added that even the geometry of the piece in Tensile (or compressive) mode, add to weaken the part compared to the "true" bulk yield stress of the material.

The technique will not replace the need to test larger parts and the need to understand where the defects affect the working of the part differently in a compressed or tensile mode. However, it is strongly believed that obtaining a somewhat "macro defect" free yield stress of the material is a crucial part to understanding the ultimate strength of the material. With other advantages such as easy sample preparation and the test can be done on small parts (1mm) in less than 1minute.Tests can be done on coatings or micron level thin walls with smaller tips down to 5micron.

CONCLUSION

In conclusion, we have shown how the Nanovea Mechanical Tester, in Microindentation mode, can be used to precisely measure the Yield Strength on a wide range of bulk materials using a cylindrical flat tip with a known area. Results obtained directly match Yield Strength data obtained using the traditional tensile testing technique. By use of this patent pending method, through Nano or Microindentation, the door has now been opened for a more precise yield strength measurement. This method provides the precision needed to allow for yield strength measurement of micro sized localized areas, small and diverse shaped samples, coatings and films. Yield Strength measurement has never been easier, more precise and capable on a wider range of sample types, sizes and shapes until now. Learn More about the Nanovea Mechanical Testers