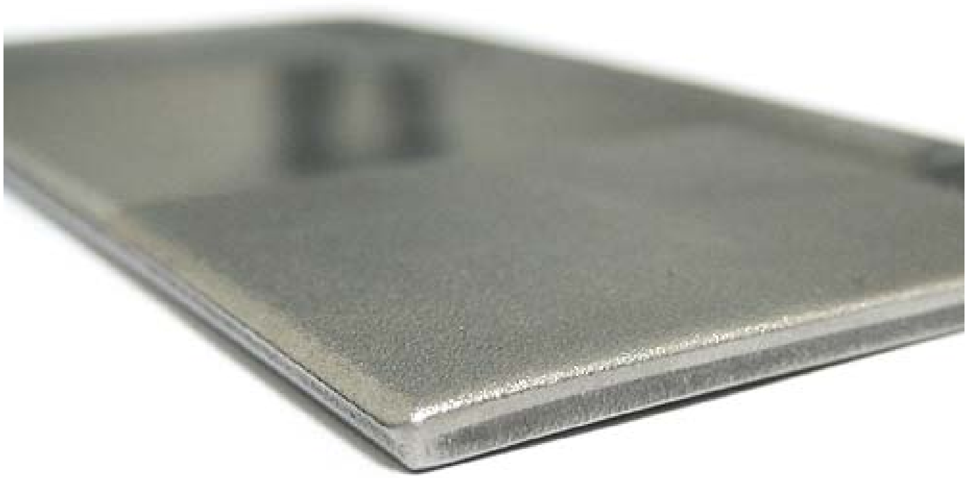
NANOVEA®
A Better Measure.

NANOINDENTATION ON SHOT PEENED STEEL



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INTRO

Shot peening is a cold working process that hits a metal surface with controlled shots to produce plastic surface deformation. It creates a compressive residual stress layer and alters the surface mechanical properties. Shot peening is widely used in aircraft repairs to relieve undesired tensile stresses built up and avoid initiation and propagation of microcracks on the surface. Understanding the mechanical properties of the shot peened surface is vital to meet requirements of targeted applications such as aerospace, medical and automotive industries.

IMPORTANCE OF NANOINDENTATION FOR SHOT PEENED SURFACES

Traditionally, the Rockwell hardness test has been used to evaluate shot peened surfaces. However, Rockwell indents usually exceed 100's of microns in depth while the peened depth is only in the range of around 25 microns. The large indenter size and the high load applied in Rockwell micro hardness measurements make it unreliable and challenging to evaluate the mechanical properties such as hardness and Young's modulus of the surface impacted by the peening process without the influence of the substrate. Nanoindentation, in comparison, measures load-displacement curves from which hardness and elastic modulus at depths under a couple of microns are directly calculated, allowing users to study this effect of shot peened surface without the influence of untreated zones.

MEASUREMENT OBJECTIVE

In this application, the Nanovea Mechanical Tester, in Nanoindentation mode, is used to comparatively study the mechanical properties of the shot peened surface versus an untreated surface.

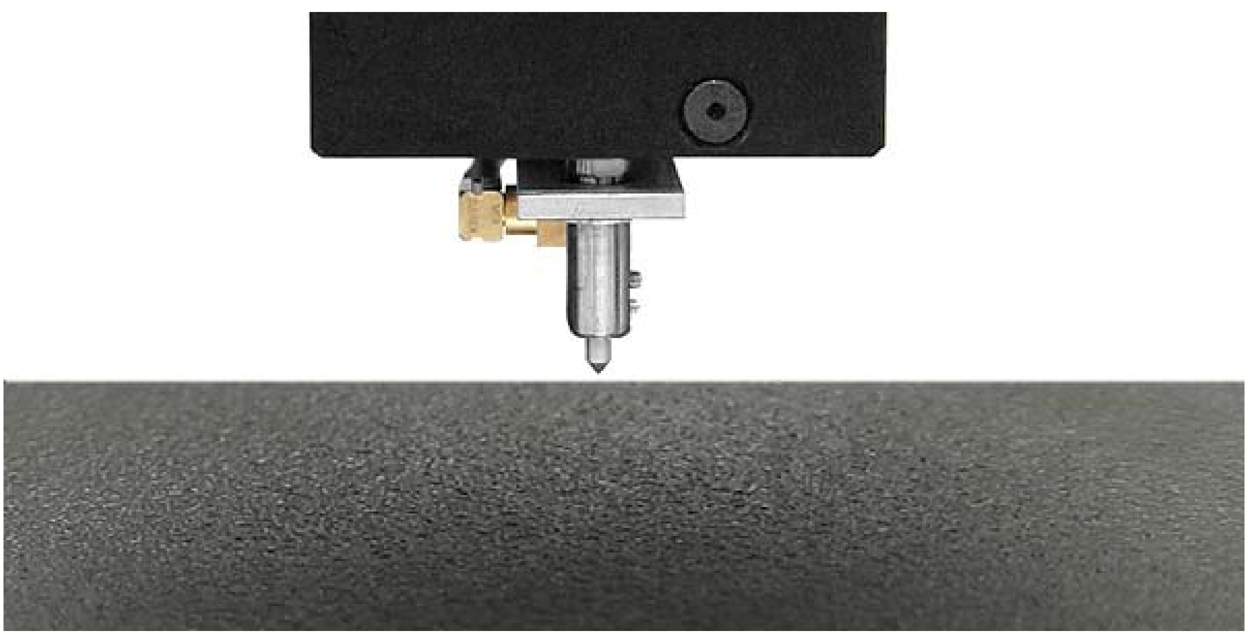


Fig. 1: Nano indenter on the shot peened surface.

TEST PROCEDURES

Nanoindentation tests were performed on a steel sample with two specific zones: shot peened area and untreated area. More than five indentations were repeated to ensure reproducibility of the test results. The following indentation parameters were used:

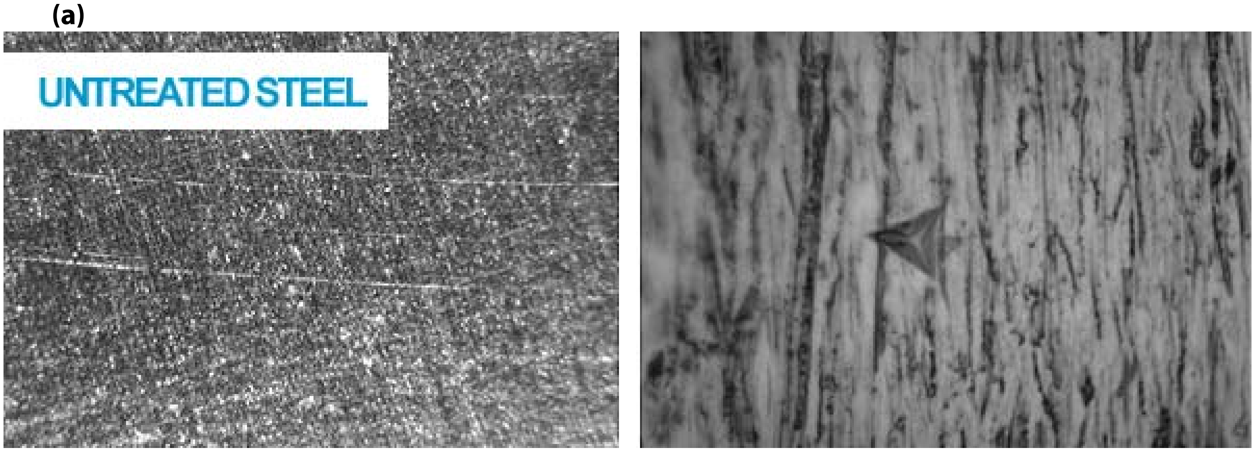
Applied Load (mN)	200
Loading rate (mN/min)	400
Unloading rate (mN/min)	400
Indenter type	Berkovich

Table 1: Indentation test conditions.

RESULTS AND DISCUSSION

The conditions of the untreated and shot peened steel surface areas are compared in Fig. 2. The untreated steel surface has directional machine marks, the groove bottom of which may act as stress concentration spots and facilitate fatigue crack initiation and propagation. Cut wire shot peening eliminates such tool marks, surface defects and isotropy by bombarding the steel surface with shot of sufficient force to create plastic deformation. It induces compressive stress on the sample surface through Hertz pressure and skin elongation. The 3D surface morphology of the shot peened steel surface is shown in Fig. 3. It is important to find a relatively smooth area to position the indenter for nanoindentation on rough surfaces to ensure reproducibility of the tests. In this study, the precision position control of the sample stage and high resolution microscope of the Nanovea Mechanical Tester allowed us to perform nanoindentation in the smooth areas on the crests of the shot bumps (as highlighted in Fig. 3).

(a)



(b)

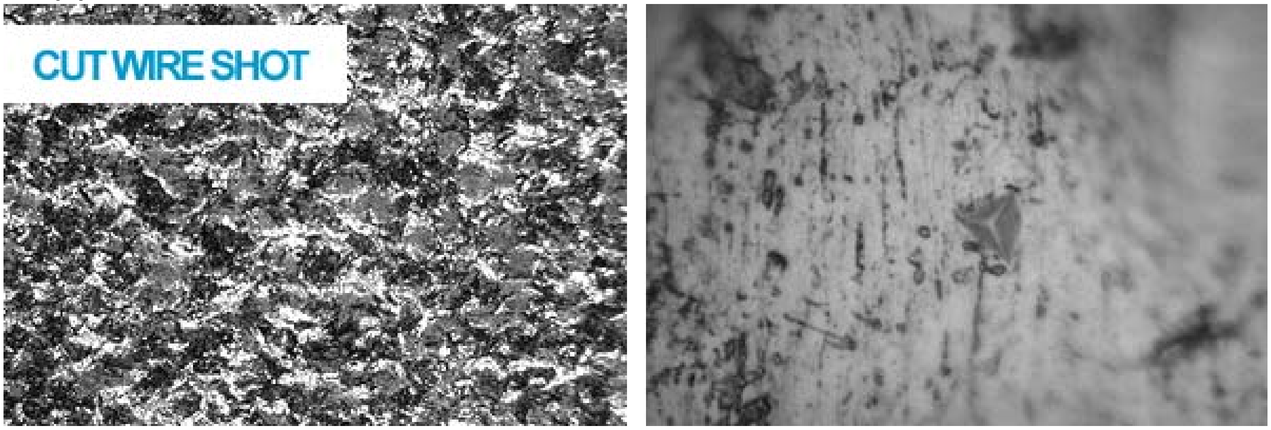


Fig. 2: Surface morphology and indentation of the untreated and shot peened steel surfaces.

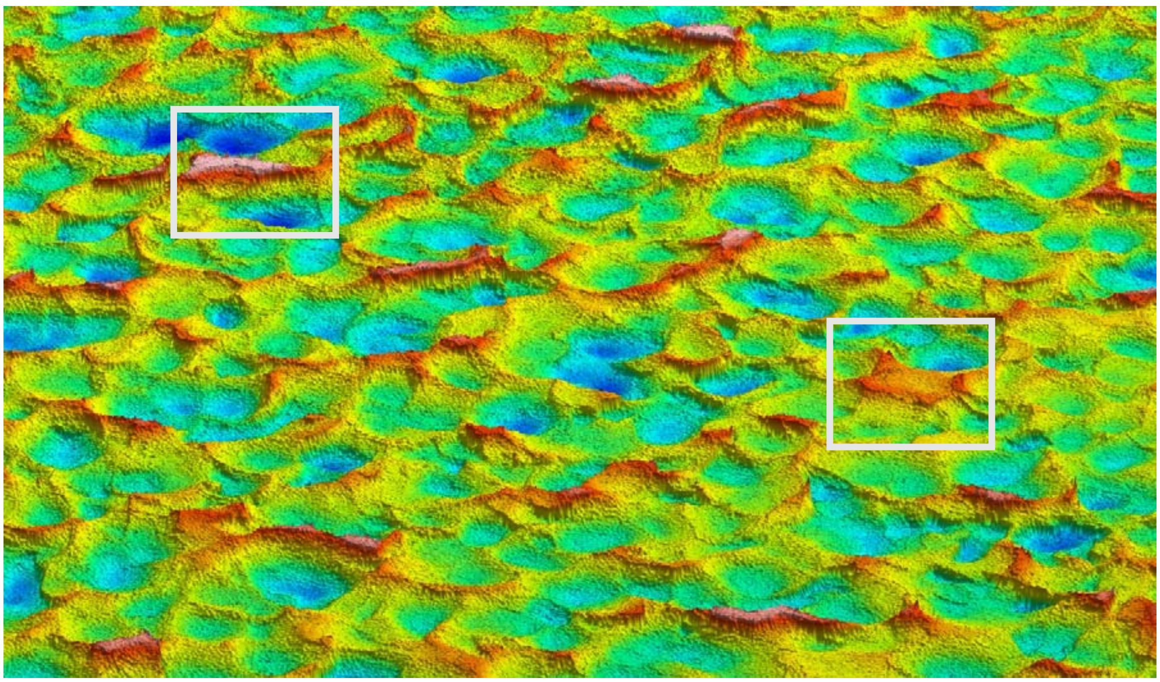
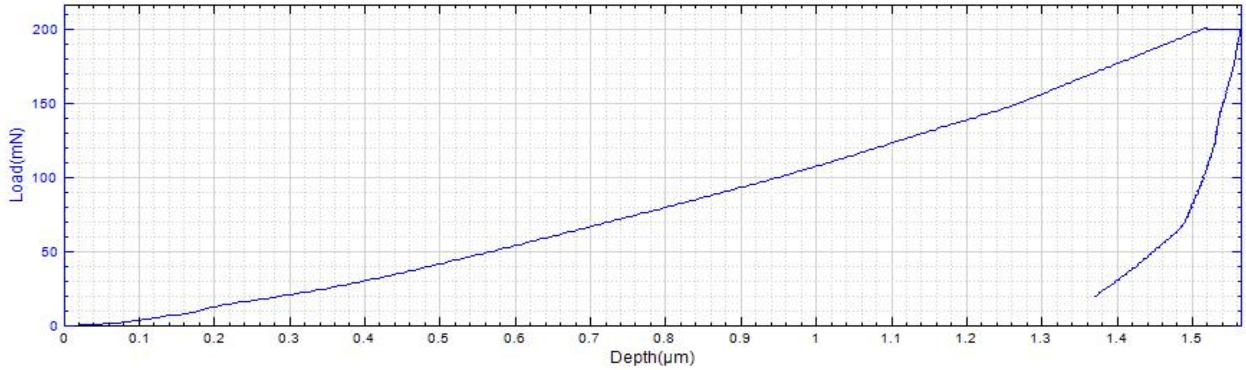


Fig. 3: 3D Surface morphology of the shot peened steel surface.

The indents under the microscope are shown in Fig. 2 and the load-displacement curves are compared in Fig. 3. The hardness, *H*, and Young's modulus, *E*, calculated from the load-displacement curves are summarized in Table 2. The shot peening process significantly increases the *H* and *E* values from 3.6 to 6.7 GPa and from 275 to 609 GPa, respectively, compared to the untreated steel surface. The variation of *H* and *E* values on the shot peened surface is related to the non-uniformity of the compressive stress distribution at different locations. It is noted that the penetration depth of nanoindentation is below 2 μm, way below the peened depth of ~25 microns, making nanoindentation a more proper technique to evaluate the mechanical properties of the shot peened metal surface without the influence of the substrate.

(a) Indentation on untreated surface:



(b) Indentation on shot peened surface:

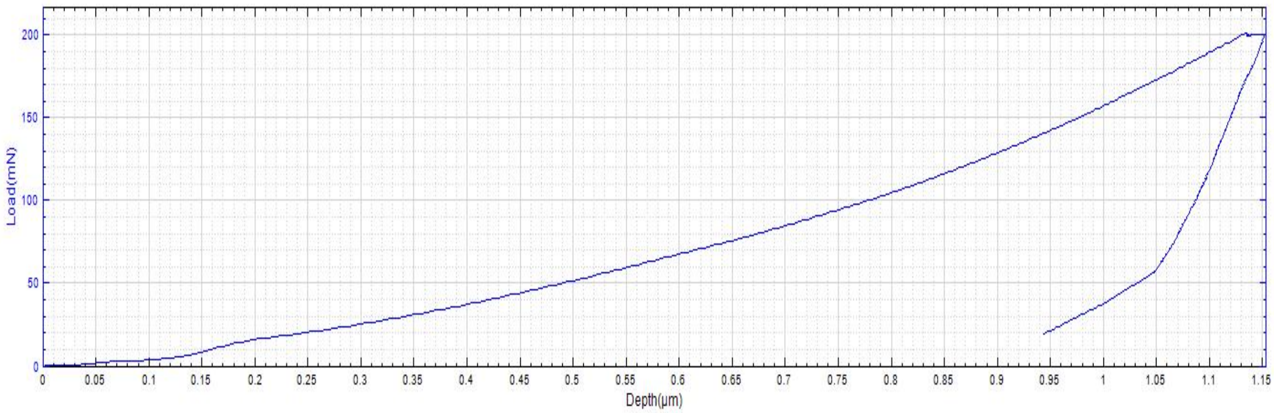


Fig. 4: Load-displacement curves of the untreated and shot peened steel surfaces.

	Untreated surface		Shot peened surface	
	Average	St Dev	Average	St Dev
Hardness (HV)	344	18	636	53
Hardness (GPa)	3.6	0.2	6.7	0.6
Young's modulus (GPa)	275	28	609	76
Depth (nm)	1576	35	1162	48

Table 2: Summary of the Hardness and Young's modulus of the untreated and shot peened steel surfaces.

CONCLUSION

In this application, we have shown that the shot peening process can significantly enhance the hardness and Young's modulus of the steel surface. Nanovea Mechanical Tester, in Nanoindentation Mode, is an ideal tool to evaluate the mechanical properties of the shot peened metal surfaces. The combination of precision position control and high resolution microscope allows nanoindentation at a proper area.

The Nano, Micro or Macro modules of the Nanovea Mechanical Tester all include ISO and ASTM compliant indentation, scratch and wear tester modes, providing the widest and most user friendly range of testing available in a single system. Nanovea's unmatched range is an ideal solution for determining the full range of mechanical properties of thin or thick, soft or hard coatings, films and substrates, including hardness, Young's modulus, fracture toughness, adhesion, wear resistance and many others.

In addition, optional 3D non-contact profiler and AFM Module are available for high resolution 3D imaging of indentation, scratch and wear track in addition to other surface measurements such as roughness.

To learn more about Nanovea Mechanical Tester or Lab Services.

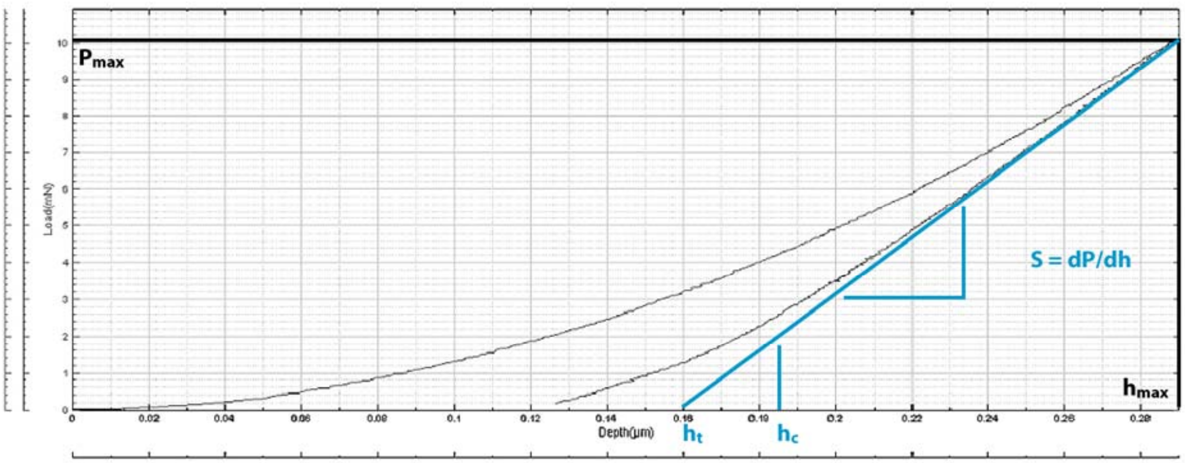
APPENDIX: MEASUREMENT PRINCIPLE

Nanoindentation is based on the standards for instrumented indentation, ASTM E2546 and ISO 14577. It uses an already 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 complete relaxation occurs. The load is applied by a piezo actuator and the load is measured in a controlled loop with a high sensitivity load cell. During the experiment the position of the indenter relative to the sample surface is precisely monitored with high precision capacitive sensor.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. Nanoindentation is especially suited to load and penetration depth measurements at nanometer scales and has the following specifications:

Maximum displacement (Dual Range)	: 50 µm or 250µm
Depth Resolution (Theoretical)	: 0.003 nm
Depth Resolution (Noise Level)	: 0.05 nm
Maximum force	: 400 mN
Load Resolution (Theoretical)	: 0.03 µN
Load Resolution (Noise Floor)	: 1.5 µN

Analysis of Indentation Curve

Following the ASTM E2546 (ISO 14577), hardness and elastic modulus are determined through load/displacement curve as for the example below.



Hardness

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

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

Young's Modulus

The reduced modulus, E_r, is given by:

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

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 ν_i are the Young's modulus and Poisson coefficient of the indenter and ν the Poisson coefficient of the tested sample.

How are these calculated?

A power-law fit through the upper 1/3 to1/2 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:

$$h_c = h_{\max} - {3P_{\max}}/{4S}$$

The contact Area Ac is calculated by evaluating the indenter area function. This function will depend on the diamond geometry and at low loads by an area correction.

For a perfect Berkovich and Vickers indenters, the area function is $A_c=24.5h_c^2$ For Cube Corner indenter, the area function is $A_c=2.60h_c^2$ For Spherical indenter, the area function is $A_c=2\pi Rh_c$ where R is the radius of the indenter. The elastic components, as previously mentioned, can be modeled as springs of elastic constant E, given the formula: $\sigma = E\varepsilon$ where σ is the stress, E is the elastic modulus of the material, and ε is the strain that occurs under the given stress, similar to Hooke's Law. The viscous components can be modeled as dashpots such that the stress-strain rate

relationship can be given as, $\sigma = \eta \frac{d\varepsilon}{dt}$
where σ is the stress, η is the viscosity of the material, and dε/dt is the time derivative of strain.

Since the analysis is very dependent on the model that is chosen. Nanovea provides the tool to gather the data of displacement versus depth during the creep time. The maximum creep displacement versus the maximum depth of indent and the average speed of creep in nm/s is given by the software. Creep may be best studied when loading is quicker. Spherical tip might be a better choice.

Other tests possible includes the following:
Stress-Strain, Yield Strength Creep, Compression strength and Fatigue testing and many others.