Advanced Material Properties Measurements with Optical Metrology

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ABSTRACT

Materials are advancing at a record rate, with unimagined complexity even in now standard materials. Traditional measurement tools can only get approximate material properties. Core to all proper design and accurate computer modeling is a base understanding of accurate material properties.

Full-field optical measurement tools using 3D digital image correlation (DIC) is able to provide a more complete measurement and analysis of these advanced materials, providing precise material properties at all scales. This paper will review microscopic analysis of crystalline behavior, coupon testing of dog bone specimens and large scale materials measurements in stamping operations. In addition, the measurement of extreme materials properties, such as high-speed forming limit curves and deep drawing properties will be discussed. Key to all of these measurements are the associated standards that control them; these will be discussed.

INTRODUCTION

Computer models have achieved great predictive power, but without precise material properties, the models will never fulfill their accurate modeling potential. Understanding the complex response of materials in order to fully understand their properties is critical for the refinement of design and manufacturing with all materials. 3D Digital Image Correlation (DIC) provides full-field 3D deformation and strain measurement, allowing for a more complete understanding of complex material responses. You may be thinking of complex composite structures, but even simple homogeneous materials benefit from these measurements. In addition, simple test machine head alignment can greatly skew the measurement data, but is easily detected and optimized with these full field measurements.

3D optical metrology in its simplest form uses photogrammetry to locate points in 3d space by triangulation, just like our eyes using stereo imaging can locate and track points in 3D space; imagine a baseball player hitting that 90mph ball out of the park. A 3D photogrammetry system, like the PONTOS system, can locate points in 3D space to the micron level, quantitatively by just using camera images.

Optical metrology in engineering design and materials properties determination using 3D Image Correlation, reduces the needs for mechanical gauges and greatly increases the quality and quantity of the data collected, all in a fraction of the time. 3D Image Correlation, using the ARAMIS system, is a highly versatile measurement method that provides 3D deformation and strain measurement over the complete surface of the material(s). For materials properties, precision measurements of r- & n-values, complete forming limit curves and deep drawing material values are easily achieved. For systems, the real full-field deformation and strains of all of the interrelating materials can be directly compared to the computer FEA models for model optimization and validation, as well as design verification and fatigue analysis.

Forming verification with optical metrology, directly comparing against the engineering FEA computer model of stampings and hydroforms, gives manufacturing direct control of its operations with better data. ARGUS is a photogrammetry system that provides this automated circle grid type analysis. This full-field analysis directly compares the entire formed part to the FEA model, measuring principle strains, material...
thickness, material flow and forming limits, just by taking some pictures. The forming analysis photogrammetry system can directly compare the entire real part with the engineering design FEM & CAD, and automatically outputting the complete data into the company’s quality control system. This automated forming analysis saves hugely on manufacturing iterations caused by missed high strain areas, and unanticipated thinning. A key to automated forming analysis is that it performs identically, globally, and directly exports results into the quality control system, for global control.

Modal analysis, NVH and large area deformation studies are simple with a dynamic photogrammetry system like PONTOS. 3D photogrammetry provides the 3D coordinates of precision dot stickers on completed assemblies, replacing mechanical gauges such as LVDTs, clip gauges and accelerometers, with nothing to fixture, wire-up and troubleshoot. Instead of a few measurement points, believed to give the desired results and days to instrument, photogrammetry targets can be placed where ever data is desired and more, with no additional effort. Components can be analyzed in hours with full 3D data, simplifying the true understanding of component assembly response, providing all desired data for precise engineering comparison with design.

Optical metrology offers new ways to greatly improve the quality and efficiency of design and manufacturing optimization for leaner, smarter operations.

**Tensile and Compression Testing**

The standard material properties testing with a test machine includes tensile and compression testing, and extending to shear, torsional and biaxial testing. These are all ideally suited for the 3d image correlation method, which follows ASTM Standards. Variations include bulge testing for automated forming limit curve measurement, to deep drawing materials studies, providing measurement abilities not possible with traditional methods. The method becomes critical in anisotropic materials such as composites to biomaterials, where the single point or average measurements mean very little.

Even on simple rolled Al sheet for the auto industry, the anisotropy defines the material properties (Hall-Peche Effect) as well as transverse rolling weaknesses (Figure 1). The industry is only just beginning to fully understand it. The ARAMIS system connects to the testing machine, reading the load and displacement of the crosshead (8 A/D channels) and its data collection is fully programmable (re: image every 100 lbs). Most 3D DIC tests consist of 30 - 300 image pairs or stages. Each stage consists of two camera images (right/left) and a calibration file that relates them. Each stage result is the 3D coordinates of 10,000+ facet points (targets, nodes) across the surface of the specimen. Each facet point is like one end of a clip gauge, a strain rosette node, and an LVDT. ARAMIS then tracks these points throughout the test, so their complex 3D deformations and strains are measured, calculating the true strain tensor for every point (see Figure 2).

Shear strains are typically quite difficult to measure locally or more importantly over larger areas; for 3D image correlation it is quite easy to measure true shear strains across entire structures, from tissues to bridges. Using a matrix of facets separated by a few pixels each, shear strain can be measured just like computer models calculate it (see Figure 3). Actually, ARAMIS provide computer model data of your real test articles and can directly compare these results against your finite element analysis. Composites are ideal applications; Jack Coate (Air Force Research Lab) said, "How could we measure it any other way?"

This becomes particularly important for model validation. The full-field ARAMIS data shows the real local deformation and strain variation, as well as the locations of maxima and minima. This is critical information for model iteration, typically of boundary conditions, and for the FEA validation. A model iterated to match the real sample becomes a much more accurate analysis, allowing advanced simulations to model the real material responses. This is a critical step towards the next advances in design and manufacturing. For example, the result image shows the comparison of a complex X-joint loading (see Figure 4).
Forming Limit Curve Measurement

When evaluating the forming process, the forming limit diagram is a critical measurement. In this diagram, the deformations resulting from the forming process are compared to the material characteristics, the so-called forming limit curve. Each material has an individual forming limit curve. The accuracy of this forming limit curve is as important as the deformation measurement itself. Normally, the forming limit curve is determined according to Nakazima or Marciniak methods, during deep-drawing tests of test material. Using a 3D image correlation system and interfacing it to a special deep-drawing machine, true forming limit curves can be determined automatically. The system is designed in such a way that the measurement device does not interfere with the handling of the machine. An optimized lighting is realized by a central projection unit to allow both cameras to record the specimen during the deep drawing process inside the machine.

These specimens can be patterned with a regular dot structure or a stochastic (random) dot pattern. The random pattern is easier to apply, and typically provides a higher measuring accuracy, and typical examples are seen in Figure 6 below.

Both cameras record the test online and automatically with the maximum recording frequency of the camera system activated in the loaded area just before the specimen fails. During the test, the measuring system records measuring parameters of the testing machine such as force and displacement, and thus can be controlled by the machine. Or, real-time 3D measurement results, outputted as analog values, can be used to control the testing machine.

Then, the images are further processed depending on the evaluation method. As for testing objects, here 3D coordinates of the specimen surface result as well with a high density of typically 0.5mm to 1mm node spacing. At each node point, 3D coordinates are measured, and major and minor strain is calculated, as well as thickness reduction. The entire image sequences can be evaluated showing the load- or displacement-dependent deformation development as a result. Alternatively, images of a loading stage before or after a crack can be evaluated. Forming Limit Curves are automatically calculated even at high forming rates, critical for strain-rate dependent materials such as high-strength steels.
Based upon the guidelines for the Nakazima tests, designed by the IDDRG (Nakazima Workgroup), the appropriate deformation stage is selected and evaluated using sectional information. The characteristic value, i.e. maximum acceptable deformations of the sample are determined and lead to one value of the forming limit curve of the corresponding material, including the statistical information over the sample group, as multiple samples of the same geometry are used. All required geometries together then create the forming limit curve.

Most steps in the described process of creating a forming limit curve can be automated: The testing machine controls the image acquisition. Thanks to a predefined evaluation approach, the selection of the deformation stage and the derivation of the FLC runs automatically in a very short time. The use of a random pattern and digital image correlation deliver a high resolution of the results.

Deep Drawing Material Testing

In addition to determining the forming limit curves, the 3D Image Correlation system can also be used for full-field measurements in deep drawing tests for the extended determination of flow curves and normal anisotropy. A particular advantage compared to standard measuring procedures is the high local resolution and the small measuring length for determining the strain. Thus, the necking area can be considered with high resolution. Yield curves (true-stress vs. true-strain curves) describe a material’s work-hardening behavior during forming and are thus indispensable for all FE forming simulations. The most common and, at the moment, only standardized test for yield curve determination is the tensile test. The tensile test, however, has the disadvantage that only a relatively small degree of deformation can be achieved before fracture occurs. This is caused by the uniaxial stress state. Multiaxial stress states are present in nearly all industrial forming processes, resulting in a much higher degree of deformation than achieved in tensile tests. Therefore, for the simulation of such forming processes, an extrapolation of the measured yield curve is required but not permitted by metal physics. However, by using a hydraulic stretch-drawing test (i.e. bulge test) combined with an online strain measurement system, yield curves can be determined to a far higher degree of deformation than in tensile tests. This leads to a significantly improved description of the yield curve and makes extrapolation largely unnecessary.

To exploit the great potential of such a combined measurement system, an IDDRG working group developed a method which facilitates the measurement of the pressure, dome height, dome curvature and the equivalent strain at the apex of the dome as a function of time and allows a very quick and easy determination of the biaxial yield curve. The yield curves from the bulge test lead to a considerably higher degree of deformation (up to 6 times higher) than that can be achieved in the standard tensile test. Therefore, the bulge test combined with the online strain measurement system ARAMIS provides an excellent new testing method for providing material data for a more effective numerical analysis.

Figure 7 - Major strain diagram versus time – The points correspond to the images recorded during the test.

Yield curves describe a material’s work hardening behavior during forming and are therefore indispensable for FE forming simulation. The tensile test is used as initial test to fit the parameters of the different equations used to describe the yield curve. Since multiaxial stress states are present in most industrial forming processes, larger strains are required in FE simulation than those reached in the standard tensile test. The different equations used to describe the yield curves are therefore used in an extrapolated condition and do...
often not fit exactly with reality at large strains. A variety of different equations and weighted sum of equations were proposed but the requirement for better experimental stress-strain curves is still very high because extrapolation leads to significant uncertainties.

The working group perfected the measurement of pressure, dome height, dome curvature and equivalent strain at the apex of the dome as a function of time. This combined Bulge-Test/ARAMIS System allows a quickly and accurately to determination of the biaxial yield curve which, for example, can be used for the following purposes:
- Quality assurance of ongoing production
- Comparison of the work-hardening behavior of different materials
- Provision of reliable yield curves for more effective numerical analysis of material behavior in forming processes
- An interim IDDRG standardization procedure defined and is being standardized
- Round robin testing following the standard produced reproducible results in four different laboratories.

Residual Stress Measurement

One of the more widely used methods for determining residual stresses is blind hole drilling. When material containing residual stresses is removed by a small, shallow hole, the remaining material adjacent to it deforms in response to the localized stress relief. Strains associated with the stress relief are measured with special rosettes designed specifically for use with hole drilling. Residual stresses can then be computed from the strains. Although used successfully in numerous applications over the years, the strain rosette version of the method has several drawbacks, such as (a) the need to install a rosette and precision milling guide, which is time consuming and limits locations that can be investigated to those receptive to a rosette and milling guide and (b) inaccuracies introduced by a hole drilled even slightly off-center in a rosette or by thermally-induced apparent strains (unless properly taken into account).

During the past two decades, optical techniques have been used in conjunction with hole drilling to determine residual stresses from surface displacements (or strains), thereby replacing the need for rosettes and milling guides. The optical techniques have included holographic interferometry, ESPI, Moire interferometry, interferometric rosettes and shearography. Although they can overcome a number of the drawbacks associated with conventional strain rosette-hole drilling, interferometric methods require adequate vibration stability. This has generally restricted the use of “optical-hole drilling” methods to laboratory environments. 3D image correlation using ordinary white light illumination offers the ability to measure micron sized surface displacements caused by hole drilling without the need for vibration isolation. Residual stresses can then be determined from the displacements.

For the image correlation-hole drilling tests, stochastic patterns of dots were applied to regions on a specimen (each approx. 10 x 10 mm) to be drilled. Specimens rested on a table with no vibration isolation. Next, the image correlation system was calibrated for the field of view of interest. A small NIST-traceable panel containing a regular pattern of dots was used. A sequence of images of the panel at different distances from and different orientations relative to the cameras were recorded to provide input to the calibration processing. Prospective hole locations within the regions to be tested were marked with a pencil spot and labeled nearby for identification. A reference image pair of a given region was then captured. Next, the test specimen was removed from the field of view and taken to another location, where a hole of 3.18 mm was drilled to a depth of 3.82 mm, using the same milling fixture employed for the holographic-hole drilling tests. The specimen was then placed back at its original location, and an image of the region around the hole recorded. The ability to remove and return a specimen was done as a check on the robustness of the ability of the image correlation system to determine hole drilling induced displacements. It should be noted that, in general, it would not be necessary to do hole drilling at a location out of the field of view. With a suitable high speed drilling fixture, a hole could be produced with a specimen kept in place.

The image correlation software automatically calculated full-field radial displacements as well as x and y (in-plane) and z (out-of-plane) displacements. The displacement data were initially dominated by rigid body motion of the specimen representing the difference in locations of the specimen relative to the cameras before and after hole drilling. The image correlation system corrected for that motion, revealing the displacements associated with stress relief produced by introduction of a hole. Next, a global transformation of the x,y,z coordinate system used in the image correlation was performed to make the origin coincide with the center of a hole at the surface of the specimen. The image correlation software was then used to create a circle with a radius 1.5 times the hole radius and concentric with the actual hole. Values of radial displacement were obtained every 15 degrees around the circle, giving a total of 23 data points. (Had it been desired, additional data could have been gathered using smaller angular increments. With the facet size and step used in these tests, a contiguous circular section line at 1.5 times the hole diameter results in approximately 200 data points, or an angular increment less than two degrees.)
The stresses found by image correlation hole drilling for the equi-biaxial specimen was compared with the computed value of stress. The value of $\sigma_x$ and $\sigma_y$ was within 5% of the computed value. The respective averages of the values for $\sigma_x$ and $\sigma_y$ were within 1% for the holographic tests. For the image correlation tests, the average of $\sigma_x$ values was within 1%, while the average of the $\sigma_y$ values was within 3%. This degree of agreement is excellent in residual stress determinations. Owing to experimental and computational uncertainties, small values of shear stress were determined by both methods; the values were less than 1% of the $\sigma_x$ or $\sigma_y$ values.

It is an ideal tool to determine profiles of stress vs. depth below a surface, using incremental drilling.

1. Image correlation used in conjunction with blind hole drilling is able to accurately determine uniaxial and equi-biaxial residual stresses essentially uniform with depth in aluminum specimens.

2. Stresses determined by image correlation-hole drilling are in good agreement with those found by holographic-hole drilling.

3. No vibration isolation was needed in the image correlation-hole drilling tests. In fact, test specimens were moved between images taken before and after hole drilling, demonstrating the robustness of the method.

High Temperature Measurements

Since 3D Image Correlation is a fully optical method, non-contact operation in hazardous environments is a unique ability. Accurate high-temperature measurements are readily achieved through an oven window or in open air. As long as the cameras are not directly affected by the hazardous environment, they maintain their calibration and are accurate; light is basically unaffected by the environment. Deformation and strain measurements with 3D image correlation up to 1400ºC is typical. This equipment is being used daily for high-precision measurements of thermal expansion of low CTE ceramics to 1000ºC. Incredibly, precision materials measurements within the thrust of a jet engine thrust are performed from a 50ft boom (see Figure 9). In this case, ARAMIS Thermography combines an ARAMIS system with a high-resolution thermal camera and provides combined 3D deformation, strain and temperature data together. In addition, the strains can be corrected for thermal expansion, providing the true mechanical strains, even of complex systems, such as automotive engines.

Measurement of an open air induction heated bi-metallic component was achieved using highpass infrared filters called heat filters and other techniques. The result below shows the shape of the part and the strains from the tensile load at temperature (see Figure 10).

The image correlation method is also regularly used through oven windows. Under these conditions, the oven window becomes part of the optical system and needs to be part of the system during calibration. The key requirement to operation in a hazardous environments in that the surface coating on the material must be able to survive the hazardous environment. Fortunately, the specifications of a measurement coating is quite broad and really only needs to have some amount of contrast and good detail.

Large Scale Structural, Modal Analysis & NVH Testing

April 2010, four ARAMIS image correlation systems were used on the critical Boeing 787 static test to 150% operational load, the largest test of its kind ever performed, with over 9,000 wired strain gauges. The 3D image correlation systems provided an additional 50,000 optical strain gauges covering four critical areas of the wing root. These critical measurement areas were around the area that had unexpectedly failed the year before, jeopardizing the entire B787 program. Image correlation is becoming a critical tool for the aviation industry. In December 2010, multiple ARAMIS systems were used on the Space Shuttle on the launch pad to confirm repair of the...
stringers on the External Tank. No other sensors were considered reliable during the cryogenic tanking test.

Bridges have different issues such as large scale deformation over time (years) and crack propagation. ARAMIS was used last year to study the shear strains in a concrete bridge that we took to failure over six hours. The deformation and cracks were monitored in real-time and with little set-up time (1 hour), versus the ~50 wired gauges that took two weeks to set up using a conventional system.

Wind energy turbines are the largest systems that we currently study, with fields-of-view of up to 100m, monitoring windmill blades in manufacturing and during operation.

The study of the loading and vibrational response is used to validate the FEA. Modal analysis and model validation are powerful applications of 3d image correlation and photogrammetry. The use of synchronized flash illumination, extends the applicability of 3D image correlation to high-speed rotating components, providing unparalleled synchronous measurement capability. The full-field vibrational or modal response of the system can be easily measured of all points simultaneously. Scanning Laser Vibrometers make huge assumptions about the phase relationship of one point to the next, many times displaying incorrect structural modal responses. Our DIC/photogrammetry software automatically detects the excitation signal and phase steps the measurement to capture all of the modal waveform.

High-speed Testing, SHB, Impact and Shock

The 3D image correlation technique is applicable to any recorded images independent of frame rate, from seconds, to microseconds to years. High-speed cameras that have the ability to capture images at 500 to 1,000,000 fps are well suited for high strain rate applications such as drop tower, crash, impact, and ballistics tests. Ultra-high-speed tests (300KHz), such as Split-Hopkinson bar and shock studies using DIC as a non-contact, full-field method, are providing a new tool for physics. The strain sensitivity of static tests (100 microstrain) is the same for high speed tests. There are, however, a different set of considerations for high speed tests. The amount of light necessary is much higher due to the significantly reduced exposure times, and the focus must be perfect to minimize blurring. In order to achieve these very high frame rates, high speed cameras reduce the number of pixels that they use, because their bandwidth is limited to so many Gbits/sec. The tradeoff for any high-speed test is the temporal resolution (frame rate, samples/sec) verses spatial resolution (pixels, no. of pixels covering the field-of-view). The faster that you want to go to capture a temporal event, such as a shockwave, the less pixels can use, reducing your spatial resolution or field-of-view.

For the Return-to-Flight of the Space Shuttle, two of the ten required steps defined by the Columbia accident investigation board were to develop current computer models for the foam impact into the carbon-carbon leading edge, etc. (previous models were from 1975) and to validate the new models with experimental tests (previous models were not validated). NASA validated and chose ARAMIS to make full-field measurements for the LS-DYNA model validations. These ballistic studies were performed at about 30,000 frames per second. Even, individual carbon-carbon fibers were measured fracturing during impact, which really helped validate the models down to the macro scale.
SUMMARY/CONCLUSIONS

3D Optical metrology with Digital Image Correlation photogrammetry is the next generation of engineering tools, replacing the majority of wired sensors with precision optical measurements. Formerly, you had to “guess” where to mount, wire and calibrate your strain gauges, clip gauges, LVDTs, etc. Since you are imaging the entire area, your sensors can be placed after the loading, when you know where you want a measurement, even a year later. DIC measures strain, in-plane displacement and out-of-plane displacement, at all points continuously. It can measure any material, from ceramics to thin films, and uniquely complex combinations of materials found in real structures. It can also measure under most stressing mechanisms, from mechanical, thermal, and vibration loading, in a fully non-contact and simple way. The data is complete and precise, and is ideal for the iteration and validation of computer models, making these models more accurate at modeling the real structures. This will take modeling and simulations for advanced designs to the next level of refinement, allowing industry to advance to a new level of capability.

Manufacturing optical measurement systems for digitizing, forming analysis and materials analysis are a becoming a part of advanced process chains for the development of products and production processes. Already today, time, costs and quality are being optimized with the use of optical metrology, thus increasing the competitiveness of our companies. These measuring technologies are used increasingly for automated inspection tasks with their further integration in processes and the availability of ever more powerful data processing systems. This data is now linked and automatically uploaded to the quality control systems for precision lean operations globally.

![Figure 14 - Forming analysis measurements now automatically download into customer's quality control system.](image-url)
REFERENCES


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DEFINITIONS/ABBREVIATIONS

ARAMIS  Advanced DIC 3D deformation & strain measurement system
ARGUS  Advanced forming analysis system
DIC  3D Digital Image Correlation
Facet  DIC measurement window (typically 15x15 pixels) & 3D coordinate point
PONTOS  Advanced 3D Photogrammetry system for dynamic measurements