Material Testing 2.0: a brief review

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Abstract

With the advent of camera-based full-field measurement techniques such as Digital Image Correlation (DIC), researchers have been trying to exploit such rich data sets through the use of more complex test configurations than the standard ones (uniaxial **tension/compression**, bending etc). This new paradigm in mechanical testing of materials has recently been christened 'Material Testing 2.0'. This paper provides a brief overview of this field which is currently seeing a large increase in research effort.

1 Introduction and background

Material Testing 2.0 (MT2.0) was first christened in a recent paper by Pierron and Grédiac [1]. It is a new paradigm in mechanical testing of materials that combines full-field deformation measurements like Digital Image Correlation (DIC), and inverse identification to extract mechanical constitutive parameters from heterogeneous (non statically-determinate) stress states. The following paper aims at providing a brief review of the existing literature, focusing on engineering materials. **There is a large area of research in MT2.0 on biological materials and tissues, but this will not be considered here. Indeed, this is a specific domain where deformation measurements are generally provided by ultrasound or Magnetic Resonance Imaging, and the inversion is very specific as tissues are generally considered incompressible. They are also generally much more deformable and are often heterogeneous. This makes the tools used to approach that problem very specific to this area and it was felt that this would deserve a specific review, so it was not included here.**

The present paper first provides a brief introduction to full-field measurements and inverse identification, though without too much detail as the objective here is not to provide a textbook on MT2.0 but a concise review. Then, existing research is reviewed and classified by type of material. The last part of the paper is dedicated to essential issues like uncertainty quantification, test design and standardization before providing a set of concluding statements. It should be noted that the first paper which defined MT2.0 [1] was about test design and did not review the whole field of MT2.0. The current paper provides the wider picture of MT2.0 while [1] focuses on a particular aspect of the MT2.0 technology.

1.1 MT2.0 vs MT1.0

Most mechanical tests currently in use in the engineering community were developed before the advent of camera-based measurements. As a consequence, they were designed so that a few pointwise deformation measurements, obtained through electrical strain gauges or extensometers, could easily be related to the global force measured by the test machine load cell. To achieve this, one needs to resort to *a priori* knowledge of the stress distribution throughout the sample. This in turn is only possible if a stress solution exists in the specimen regardless of the constitutive behaviour of the test material. Such tests are generally known under the term 'statically determinate'. The mechanical model is such that the stress equilibrium equations can be directly integrated to obtain the stress distribution. Unfortunately, this is only possible for 'simple-enough' geometries like a rectangular prismatic bar under uniform tensile or compressive pressure at its extremities, or in bending, a circular tube submitted to a uniform torque, a circular plate clamped at its boundary and submitted to an internal pressure (bulge test), to cite a few. All current test standards rely on such a paradigm, which I will call here "MT1.0" in opposition to MT2.0.

On the other hand, MT2.0 relies on more complex geometries and loadings. The consequence is that the test is not statically determinate. Therefore, it is less straightforward to relate the global load applied by the test machine to local strain measurements and inverse methods are to be used to exploit the tests. Moreover, because of the test complexity, it is necessary to perform full-field measurements using techniques line Digital Image Correlation (DIC) to have enough experimental information to proceed successfully to the data inversion. This increases the cost and complexity of the mechanical procedure, but provides a significantly richer database from which to identify the constitutive models, and

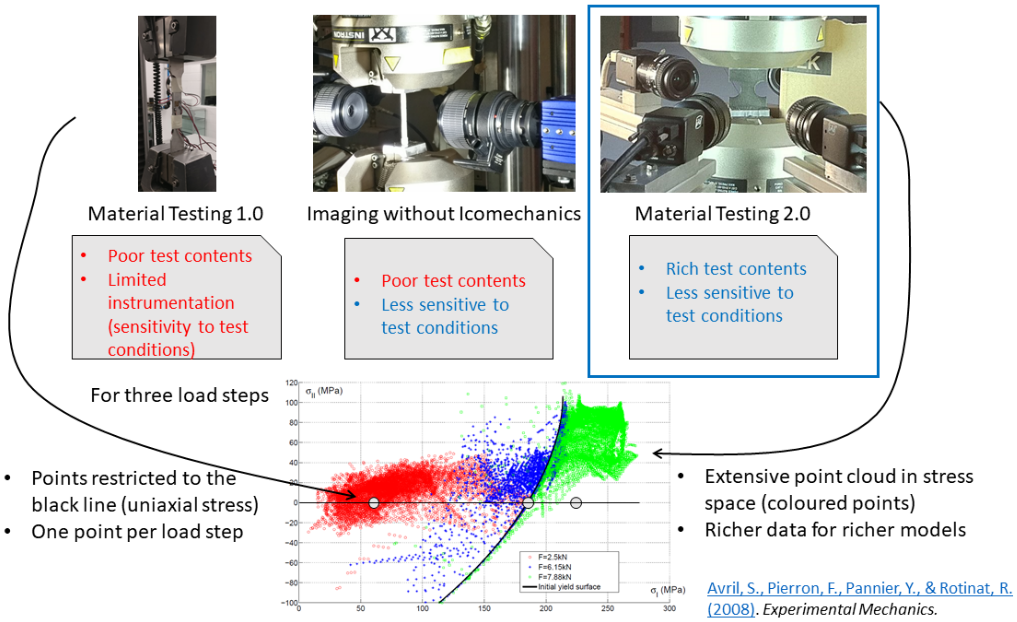

Figure 1: **MT2.0 vs MT1.0**

relaxes the need to strictly control the boundary conditions.

The two concepts are illustrated in Figure 1. The relative advantages and disadvantages of MT1.0 and MT2.0 are reported in Table 1.

1.2 A bit of history: the pioneers

According to the author's best knowledge, the very first paper that builds on the philosophy of MT2.0 dates back to 1971 introducing the idea of using finite element simulations to iteratively update material parameters to minimize a distance between experiment and model [3]. This is now known as Finite Element Model Updating (FEMU). In 1984 [4], the authors use a point load on a composite half-plane and strain gauges at different locations to identify all the orthotropic stiffnesses of a carbon/epoxy composite. Though this did not use full-field measurements, the reasoning was very much aligned with that of MT2.0. The reason why the authors could avoid full-field measurements is because they used an analytical solution to the problem (point load on an infinite semi-space). Later, they used the same procedure

	Advantages	Drawbacks
MT1.0	Simple to exploit Test standards available Inexpensive	Poor in contents Sensitive to boundary conditions Limited applicability (necking, heterogeneous materials etc.)
MT2.0	Very rich in contents (fewer tests needed) Less sensitive to boundary conditions Allows to test stress interactions Wide design space Possibility to test specimens 'as manufactured' (see [2] for instance)	Complex to exploit More expensive to set up No test standards available

Table 1: **Advantages and drawbacks of MT1.0 and MT2.0**

but on a disc in compression [5]. However, such attempts are limited to cases where there is a statically determinate stress solution which make them impractical in general.

In the late 80s, early 90s, full-field measurements started to emerge. Two groups working independently, in different technical areas, undertook pioneering work in MT2.0. In the Netherlands, the group of Cees Oomens started publishing work mostly focusing on biological membranes combining digital marker tracking (an ancestor of DIC) and FEMU. Their first published study on the topic was released in 1988 [6] and a series of work followed [7, 8, 7, 9]. Simultaneously, and independently, Michel Grédiac approached the same problem but for the simultaneous identification of the whole set of orthotropic stiffnesses of polymer matrix composite plates [10]. In the process, he devised what was to be called later the Virtual Fields Method (VFM) [11], an alternative to FEMU as proposed by Kavanagh and Clough [3]. FEMU and the VFM (with all their variations) are now the two most used techniques to invert full-field kinematic data to obtain mechanical constitutive properties of materials.

1.3 Full-field measurements

Full-field measurements started a long time ago using light interferences. For instance, the famous experiment by M.-A. Cornu [12] allowed for very accurate measurement of Poisson's ratio of glass. Over the years, different set-ups were used leading to techniques called 'Moiré (or grating) interferometry', 'Speckle interferometry' (or ESPI), 'Shearography' and 'Holographic interferometry' for the most popular. They were dominant until the end of the 20th century and used in some early MT2.0 studies but have now fallen from grace because of their cost and difficulty of use.

With the development of high-performance computing, techniques based on light intensity imaging (also known as white light imaging) have boomed because of their relative ease of use and lower cost. The most widespread currently is the so-called 'Digital Image Correlation' (DIC) technique [13]. An alternative method based on grid or chequerboard patterns, denoted either 'Grid Method', 'Sampling Moiré' or 'Local Spectrum Analysis' [14] is also used in many MT2.0 articles.

Full-field measurements are key to MT2.0 as they provide the wealth of kinematic information that is needed when no closed-form solution to the stress problem is available. However, they need to be used in a quantitative manner which requires a thorough understanding of their metrological properties. The guide of good practice released by the International DIC Society [15] is a useful document in that respect. A recent article by Michel Grédiac's group also provides some very useful insight [16].

1.4 Inverse identification techniques

Before the democratization of DIC, the literature on the use of inverse methods to identify material mechanical parameters from full-field measurements was rather scarce. Indeed, such measurements were confined to specialized labs, generally focusing on optical engineering and not on mechanical identification. As stated in Section 1.2, two methods emerged at the time: Finite Element Model Updating (FEMU) [3] and the Virtual Fields Method (VFM) [17], which are currently the two mainstream techniques. There are however many others in publications, some different, some just variations of FEMU and the VFM. There are also sometimes different names for the same type of technique. The first attempt to classify the methods was published in 2008 [18]. Apart from FEMU and the VFM, the paper identifies two

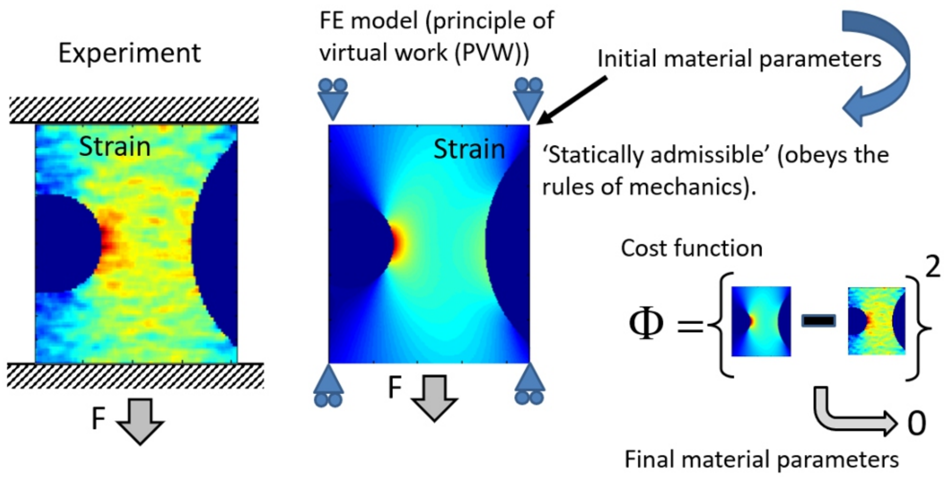

Figure 2: Finite Element Model Updating (FEMU)

other techniques of practical use for MT2.0: the Constitutive Equation Gap Method (CEGM) [19, 20] and the Equilibrium Gap Method (EGM) [21]. Both are direct or semi-direct methods like the VFM, while FEMU is iterative in nature. The CEGM relies on the parametrization of the stress field (using Airy stress functions for instance, as in [19]), while the EGM is a particular case of VFM with local virtual fields.

Finite Element Model Updating (FEMU) arises from a natural idea: minimizing the distance between simulated and measured kinematic quantities like displacement or strain. The initial idea can probably be traced back to Kavanagh and Clough [3], to the best knowledge of the present author. FEMU was used extensively in the field of structural dynamics using discrete sensors (accelerometers). For MT2.0, significant work started in 1993 [7] and grew regularly in the 2000s. Different types of cost functions have been devised and some in-depth discussion about this can be found here [22]. It is worth noting the so-called Integrated DIC (I-DIC) approach which solves the image correlation problem with the material parameters as unknowns without the requirement to explicitly calculate displacements from the acquired images [23, 24]. A schematic of the principle of FEMU is provided in Figure 2.

The Virtual Fields Method (VFM) is an alternative developed in the late 80s [11]. Instead of recalculating statically admissible mechanical fields from geometry and boundary conditions to provide data to compare with measurements, the VFM uses the measured strain field and an assumed constitutive model to reconstruct stresses, see the schematic in Figure 3. The principle of virtual work (PVW) is then used to check for static admissibility of these reconstructed stress fields. For constitutive models that depend linearly on the parameters to identify, the problem leads to linear equations so that the selection of as many virtual fields (VFs) as constitutive unknowns leads to a direct identification provided the VFs are linearly independent from each other. For non-linear models, the PVW is used to build up a cost function that is then minimized. The theory of the VFM can be found in the VFM book [17]. Compared to FEMU, the strength of the VFM is its computational efficiency. Two published articles benchmarking the VFM versus FEMU have quoted computational times more than a hundred times lower for the VFM for hyperelastic [25] and elasto-plastic models [26]. A useful article was published in 2007 [27] demonstrating the link between the VFM and FEMU. In the case of elasticity, this article shows that the VFM is the optimal way to solve a FEMU problem when full-field measurements were available. In that situation, the iterative FEMU problem could be formulated as a direct VFM one. This result has however not been extended yet to non-linear laws. In the VFM, the choice of the virtual fields is key. For the linear VFM, noise-optimized virtual fields are generally used [28], while for the non-linear VFM, sensitivity-based virtual fields are state of the art [29], though many authors still use manually-defined virtual fields.

Finally, a new family of methods are starting to emerge, called either 'data driven identification' (DDI) or 'model discovery'. They state that the main weakness of standard MT2.0 is the need to assume an *a priori* constitutive model. The reader is referred to several recent papers on DDI [30, 31, 32, 33, 34, 35, 36]. Another interesting approach on 'model discovery' consists in choosing the best model from a library of constitutive 'bricks' [37], though this technique still requires experimental validation. Finally, a numerical integration scheme was proposed independently by two groups [38, 39] that relies on the co-linearity of the strain and

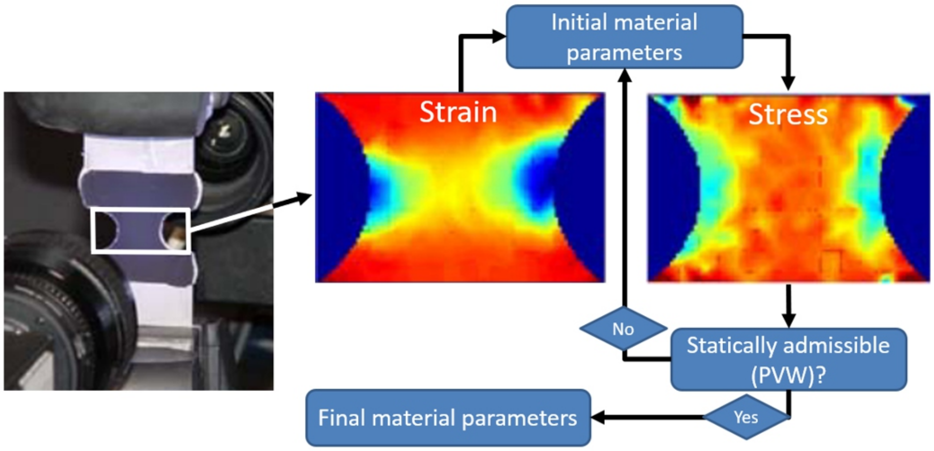

Figure 3: The Virtual Fields Method (VFM)

stress tensors (same principal directions); this therefore only applies to isotropic materials. Whether any of these techniques will ever become mainstream is difficult to say at this stage, but maybe in a near future they will be combined with more standard approaches to help discriminate the relevancy of different *a priori* models.

2 Classification by type of material

There are many ways to approach a review of MT2.0: by type of identification problem, by type of constitutive model or by type of test configuration to cite but a few. None of these offer a perfect way to navigate what has become a dense literature within the last ten years. The angle used here is the material type. This somehow maps into constitutive models (elastomers will focus on hyperelasticity while metals will deal with elastoplasticity for instance) but not always. It was decided against adding other classifications for the sake of legibility and compactness of the paper.

2.1 Polymer matrix fibre composites

There have been many contributions to MT2.0 in the field of composite materials. Indeed, the anisotropy of such materials makes them more difficult to characterize and there has been a trend towards trying to find test configurations to identify all orthotropic stiffness components in a single test. This was the object of the seminal work by M. Grédiac [10, 40] where a circular plate was tested with three different sets of bending loads which, combined together, allowed for the six anisotropic bending stiffness constants to be retrieved. A few years later, the work was extended to vibration tests, still on circular composite plates [41, 42]. In-plane properties were studied using different MT2.0 test configurations: a T-shaped specimen [43, 44], a three point short beam bending test [45, 46, 47], an unnotched Iosipescu test [48, 49, 50, 51, 52], an open-hole tensile test [53, 54] and an elliptical open hole specimen [55].

Some test configurations resulted from the geometry of an actual structure rather than flat panels. In [56, 2], a thick composite ring cut from a thick glass-epoxy composite tube was used to identify the whole set of orthotropic stiffnesses in the through-thickness plane in the cylindrical coordinate system. In [57, 58, 59], rings formed of windings of superconductive wires were tested using a similar configuration. These are called 'pancakes' and stacked together to form superconductive coils for MRI magnets. In that study, homogenised orthotropic stiffnesses were identified to validate a finite element model ensuring that the magnet would not deform too much under magnetic field to keep the spatial homogeneity of the magnetic field consistent with the requirements of MRI. In [60], a 3D woven turbine blade root was considered and the full set of orthotropic stiffnesses identified. These examples show the potential for MT2.0 to identify mechanical properties directly on the manufactured artefacts rather than on a semi-product which may not have the same properties as these are highly influenced by the manufacturing. All previous examples were concerned with linear elastic properties. Some work have included non-linear behaviour in shear, using the unnotched Iosipescu test [61, 50, 51] or the three-point bending test on a short beam [47]. In-plane damage properties were investigated on a biaxial test on a cruciform composite specimen in [21], while impact damage was revealed using bending tests, deflectometry to measure full-field curvatures and a VFM formulation for heterogeneous properties in [62, 63]. A particularly interesting case concerns high strain rate properties of composites. It is notorious that the current gold standard for dynamic testing, the Kolsky bar or Split Hopkinson bar, is not suitable to measure elastic properties of quasi-brittle materials such as composites. Recently, a stream of research has looked at designing new inertial impact tests which combined with the use of acceleration as a load cell, has led to the so-called Image-Based Inertial Impact (IBII) test. The seminal research was published in 2011 [64] and 2014 [65], leading to the following publications for both in-plane [66, 67] and through-thickness [68, 69] elastic properties.

2.2 Metallic materials

This is probably the field with the largest contribution to MT2.0. Technical areas range from structural performance (generally low strains) to forming (large strains, often anisotropic for sheet metal forming). It can include temperature or not, and can consider the time-dependence (viscoplasticity) or not.

2.2.1 Quasi-static studies

To the best knowledge of the present author, the very first study in this area was published in 1998 [8], if we note that the general FEMU process presented in [70] only relies on simulated case studies, which is less relevant to practical MT2.0. The study used marker-tracking (an ancestor of DIC) and FEMU on an asymmetrical double deep-notch (ADDN) specimen in tension. A few years later, J. Kajberg published a nice study too [71], based on an in-house DIC algorithm and FEMU. The geometry was a symmetrical double deep-notch (SDDN) tensile specimen. In the mid-2000s, the VFM was adapted to elasto-plasticity [72] and a series of initial work using the VFM was released [73, 74], based on the grid method and using first a waisted specimen and then an SDDN one. At the same time, a study on using the Constitutive Equation Gap Method (CEGM) was published [19] using a test piece with a step change in thickness. The first study on applying MT2.0 to anisotropic plasticity was published in 2010 [75] where a biaxial test specimen was used together with DIC and FEMU to obtain the parameters of an FMM anisotropic yield function [76] with a Swift hardening model. After these pioneering attempts, this technical area started booming in the 2010s and is still now the most active application area of MT2.0, most certainly because metals are by far the most used class of materials in engineering. The boom also corresponds to the spread of commercial DIC platforms, giving researchers without any initial knowledge in full-field measurements access to the technology. Tables 2 and 3 provide an overview of works in this area. Please note that studies on identification of crystal-plasticity laws from microscale measurements have been left out as this is not as such an MT2.0 approach. Finally, a short review paper on this topic is also available in [77].

Finally, a very recent paper was published that reviews test methodologies to characterize anisotropic plasticity for sheet metals [109]; it mentions some MT2.0 work.

2.2.2 High strain rate and viscoplasticity

With the technological breakthroughs in high speed and ultra-high speed cameras, extension of MT2.0 to high strain rate events has boomed in the last ten years, giving access to the exploration of viscoplastic (or strain rate dependent) behaviour of metallic materials. A pioneering study was published on this in 2004 by J. Kajberg [110]. Using an ULTRANAC FS 501 camera at an interframe time of 2 μs, he was able to image a small Symmetrical Deep Double Notch (SDDN) specimen loaded in tension using an inertial Hopkinson bar setup. He was able to identify the parameters of a Perzyna viscoplastic model by FEMU. This was followed up by a second contribution [111] using a small uniaxial specimen loaded in compression in a standard split Hopkinson bar apparatus. This time, the interframe time was 8 μs. FEMU was employed to identify the strain rate dependence of the material through a Johnson-Cook constitutive law. The results were surprisingly good considering the poor spatial resolution (images were 166 x 192 pixels), though only one parameter was identified, the strain rate sensitivity one, all the others coming from quasi-static testing. Table 4 contains a list of some references for viscoplastic behaviour identification with MT2.0.

	Yield surface / hardening law	Identification technique	Specimen type	Notes
[78]	Hill48 / Ludwik	FEMU	ADDN and SFT	
[79]	Hill48 / Swift	FEMU	SFT	
[80]	Hill48 / Ludwik	FEMU	Perforated out-of-plane	
[81]	Von Mises / Swift and modified Voce	VFM	WS	
[82]	Hill48 / Swift	VFM	OH	
[83]	Hill48 / Swift	FEMU	Biaxial	
[84]	Hill48 and Bron-Besson / Voce	FEMU	Biaxial	
[85]	Hill48 / Linear	VFM	Sigma	
[86]	Von Mises, Hill48, Bron and Besson / Modified Voce	FEMU	Biaxial	
[24]	Von Mises / Ramberg-Osgood	FEMU and I-DIC	WS	
[87]	Von Mises / Ludwik with Chaboche damage model	VFM	OH	Simulated data only
[88]	Von Mises / linear and exponential kinematic hardening	I-DIC	Biaxial	
[89]	Von Mises / linear kinematic hardening	I-DIC	Biaxial	Fillet radius optimization
[90]	Hill48 / Swift	FEMU with image deformation	OH (1 & 2 holes, diamond)	3D specimens
[91]	Von Mises / Swift	VFM	TSG	Geometry optimization
[92]	Hill48 and Yld2000 / Swift	VFM	SDDN	

Table 2: MT2.0 studies for elastoplasticity, **years 2012-2017**. ADDN: Asymmetrical Double Deep-Notch specimen, SDDN: Symmetrical Double Deep-Notch specimen, SFT: Short Flat Tensile specimen, WS: Waisted Specimen, OH: Open Hole specimen, TSG: Tensile Specimen with Grooves.

	Yield surface / hardening law	Identification technique	Specimen type	Notes
[93]	Hill48 / Swift	FEMU	Erichsen punch test	
[94]	Von Mises / Ludwik and Armstrong-Frederick (kinematic)	FEMU	Biaxial	Non-proportional loading
[95]	Hill48 / linear kinematic hardening	I-DIC	WS	Very thin sheet specimens
[96]	Von Mises and Hill48 / linear and exponential kinematic hardening	I-DIC	Small biaxial	Very thin sheet specimens
[97]	Yld2004-18p and kinematic hardening / Voce	FEMU	Butterfly	Shape optimization
[20]	Von Mises and kinematic hardening / linear hardening	CEGM	WS	Heterogeneous properties
[98]	Von Mises / Piecewise	VFM	WS	Piecewise linear hardening
[99]	Von Mises and kinematic hardening / exponential hardening	FEMU	ADDN	Optimization focused
[100]	Hill48 and Yld2000 / Swift	VFM	Biaxial	
[101]	Hill48 and Yld2000 / Voce	FEMU	Perforated out of plane (Pottier)	
[102]	Hill48 and NLKH / Swift	VFM	Bridge-like	
[103]	Yld2000/ Swift	VFM	SDDN	
[29]	Hild48 and Yld2000 / Ludwik	VFM	SDDN	
[104]	Von Mises / Linear and Swift	VFM	SDDN	
[105]	Von Mises / Kinematic hardening (Chaboche)	VFM	OH and SDDN	Ratcheting
[106]	Von Mises / Kim-Tuan	FEMU	SDDN and TSG	Matching force only
[107]	Von Mises / Swift+Voce	FEMU	MDS	
[108]	Drucker / Swift, Voce, Swift + Voce	VFM	OH, SDDN, TBS	
[36]	Non-parametric	DDI	DHS	

Table 3: MT2.0 studies for elastoplasticity, **years 2018-2021**. ADDN: Asymmetrical Double Deep-Notch specimen, SDDN: Symmetrical Double Deep-Notch specimen, SFT: Short Flat Tensile specimen, WS: Waisted Specimen, OH: Open Hole specimen, TSG: Tensile Specimen with Grooves, MDS: Multiaxial Double-notch Specimen, TBS: Twin Bridge Shear, DDI: Data-Driven Identification, DHS: Double Hole Specimen.

	Viscoplastic Model	Identification technique	Test / Specimen type	Frame rate and/or Temperature and pixel resolution
[112]	Perzyna and Yoshida	VFM	WS	5000 fps (800 x 600)
[113]	Johnson-Cook	VFM	SDDN	10,000 fps (512 x 96)
[114]	Johnson-Cook	FEMU	Plate blast	25,000 fps (512 x 512)
[115]	Johnson-Cook	VFM	Dogbone	350-900°C (2448-2040)
[116]	Johnson-Cook	VFM	3PB	5 Mfps (400 x 250)
[117]	Johnson-Cook	VFM	IBII	5 Mfps (400 x 250)
[118]	Non-parametric	VFM	IBII	5 Mfps (400 x 250)
[119]	Norton-Hoff	VFM	Dogbone, SDDN, TSG	500-800°C, 2,000 fps, (1280 x 1024)
[120]	Johnson-Cook and Lim-Huh	VFM	Dogbone	120,000 fps (640 x 128)
[121]	Johnson-Cook	VFM	Dogbone	360-500°C (2352 x 1728)
[35]	Non-parametric	DDI	NAHS	68,000 fps (2472 x 3296)
[36]	Non-parametric	DDI	DHS	68,000 fps (2472 x 3296)

Table 4: MT2.0 studies for viscoplasticity. SDDN: Symmetrical Double Deep-Notch specimen, WS: Waisted Specimen, TSG: Tensile Specimen with Grooves, MLS: Modified Lap Shear, 3PB: Three-Point Bending, IBII: Image-Based Inertial Impact test, NAHS: Notches and Hole Specimen.

It should be noted that some additional studies are available that only process simulated data [122, 123, 124, 125, 126, 127].

Finally, it is interesting to note that MT2.0 offers the possibility to identify material behaviour directly on the manufacturing process. For instance, in [128], forces and chip morphology are informing a finite element sensitivity study to investigate the influence of the different parameters of the Johnson-Cook model.

The main conclusion from this brief review for viscoplastic models is the fact that the Johnson-Cook model is mostly considered, even though it is widely regarded as not very accurate. The reason is probably that the current methodologies are still lacking in accuracy, mostly because of the need to resort to low spatial resolutions when increased camera framing rates are required. Moreover, the effect caused by this low spatial resolution is never investigated, except in a few of the studies above [126, 125, 127, 35] which use the latest state of the art FE-DIC Digital Virtual Twin (see Section 3.1) to perform a thorough error analysis.

This is clearly an area where progress is needed. One of the issues when testing at high strain rates is the difficulty associated with measuring an external load as inertia effects are generally present. There are opportunities to use the specimen itself as the load cell. For instance, in [120], a strain gauge was used in a part of the specimen that remained linear elastic. The same idea was used in [112] but the DIC data was used there. Finally, for higher strain rates, the acceleration field can be used as a load cell [118, 117].

2.3 Metallic welds

While in Section 2.2, materials were considered homogeneous at the mesoscale, there are situations where this is not true anymore. It is the case for welds, for which the thermo-mechanical history associated with the welding process affects different parts of the weld in a different way, leading to strongly heterogeneous mechanical properties. In the literature, the main experimental procedure used to approach this problem consists in either using indentation (but the hardness is a poor proxy of the full elasto-plastic response) or mini tensile tests (but this is very time consuming). MT2.0 is an elegant approach to the mapping of the heterogeneous elasto-plastic properties within a weld and a number of studies can be found in the literature on this.

To the best knowledge of the present author, the first published work on using MT2.0 on welds was released in 2008 [129]. Previously, DIC had been used to map the strains in a weld but only a uniform stress method (USM) had been used to exploit the data. Contributions to this topic are listed in Table 5.

It is interesting to note that apart from [129, 130, 131, 132, 133], all studies were published in the last three years, showing that the topic is of growing interest. It should be understood that the 2.0 nature of the tests here mainly arises from the heterogeneity of the material and that the studies all consider a simple 1D test configuration where the assumption of uniaxial homogeneous stress can be a reasonable approximation without the need for a more complex inverse identification procedure [129]. However, the real challenge is to move to more complex geometries like that of a T-weld for which an inverse routine is unavoidable. In this case, the problem of the parametrization becomes key as we cannot rely on the measured strain distribution to provide a guide for the spatial map of properties. An automated parametrization process is essential to progress towards the goal of a more generic MT2.0 tool. Some work on this is currently underway [148].

2.4 Polymers and elastomers

2.4.1 Viscoelasticity

Interestingly, there are not very many papers on MT2.0 for viscoelasticity. One of the first studies concerned the simultaneous identification of stiffness and damping (complex stiffness) of polymeric plates using inertial vibrations tests [149, 150]. An interesting features was the ability to remove any sensitivity of the results to structural damping at the connection between the plate and the shaker by removing this part from the virtual work equation with the VFM. A similar approach was used in [151, 152] but using a local fit of the equilibrium equation

	Weld type	Identification technique	Test / Specimen type	Notes
[130]	FSW	Constant stress and VFM	Dogbone butt joint	
[131]	GMAW	Constant stress	Dogbone butt joint	
[132]	FSW	VFM	Small butt joint	High strain rate
[133]	EBW	Constant stress and VFM	Dogbone butt joint	VFM recommended
[134]	LW	VFM	Dogbone butt joint	
[135]	MIGW	VFM	Dogbone butt joint	
[136]	FSW	FEMU	Dogbone butt joint	Bi-linear variation of properties along thre weld
[137]	LW	VFM	Dogbone butt joint	
[138]	FSW	VFM	Dogbone butt joint	
[139]	Heat treatment	VFM	Dogbone butt joint	Fourier VFM
[140]	FSW	USM & VFM	Dogbone butt joint	
[141]	Not specified (girth weld)	USM	Dogbone butt joint	
[142]	FSW	USM	Dogbone butt joint	
[143]	Heat treatment	USM	Dogbone butt joint	
[144]	FSW	USM	Dogbone butt joint	
[145]	MAG	USM	Dogbone butt joint	
[146]	MAG	USM	Dogbone butt joint	
[147]	FSW	USM	Dogbone butt joint	

Table 5: MT2.0 studies for welds. FSW: Friction Stir Welding, GMAW: Gas Metal Arc Welding, EBW: Electron Beam Welding, LW: Laser Welding, MIGW: Metal Inert Gas Welding, MAG: Metal Arc Welding

rather than the VFM. This however has the disadvantage of having to manipulate fourth order derivatives of the measurements, which requires strong regularization. There were some similar work extending this to sandwich and composite panels but this is outside the scope of the present review. In [153], a cube of polymeric foam was excited by a shaker in vacuum and high speed cameras used to sequentially record the deformation of the four faces of the cube. FEMU was then used to identify the complex 3D orthotropic stiffness matrix of the tested material. In [154], an ultrasonic inertial test, later christened Image-Based Ultrasonic Shaking (IBUS) test and inspired from [155], was used to identify a visco-elastic law. The principle is to excite a rectangular flat specimen inertially around its first longitudinal resonance frequency, thus establishing a vibration in the ultrasonic regime (20 kHz here). The self-heating caused by thermal dissipation provides a large data-base of temperature and strain rates. Ultra-high speed imaging coupled with the grid method and the VFM allowed to extract the variation of the modulus as a function of these two quantities. This is like a very fast DMTA test that also covers strain rates (in the 100s of s^{-1}) not available with DMTA because of inertia limitations.

Alternatives to vibration tests have also been considered. Hoshino *et al.* [156] used a waisted tensile specimen combined with different test temperatures to identify the relaxation curves of a soft epoxy (Epikote 828) using the Virtual Fields Method. The viscoelastic behaviour was parametrized with a Prony series and the relaxation curves of the bulk modulus, K, and the shear modulus, G, were successfully identified. In a similar vein, the uniaxial relaxation behaviour of a nitrile rubber has been identified in [157] by a combination of high rate wave experiments and lower temperatures, with the VFM making use of acceleration as a load cell. A similar approach was used in [158] with an Image-Based Inertial Impact (IBII) test. The underpinning idea is that the heterogeneity of the strain rate field can give access to a range of relaxation times using a Prony series. Finally, Fletcher and Pierron [159] devised a method called the IBIR (Image-Based Inertial Release) test. It makes use of a universal test machine in which a long specimen containing notches at the top was loaded in tension at slow rates. During the loading, the low strain rate stiffness can be identified, while when the notches fail, a release waves propagates downwards that can be captured to obtain high strain rate stiffness. The main advantage of this methodology is the possibility to measure stiffness at high and low rates on the same test (and the same specimen). There is potential to apply this to materials like bone to separate specimen-to-specimen variability from strain rate dependence, for instance.

As for the non-linear behaviour of polymers at larger loads, MT2.0 is nearly completely absent. It is possible however that the present author has missed some references as they may live in the rather contained community of polymer mechanics but discussions with some colleagues in this field have confirmed that this was not a widespread subject in this field. It is clearly a field where much progress would be achieved by introducing MT2.0 philosophy in the mechanical testing of polymers as models are complex and generally involve a large number of parameters (see [160] for instance).

2.4.2 Hyperelasticity

Because of the soft nature of elastomers and their capacity to deform to high levels of strain, they are natural candidates for MT2.0 as they suit DIC measurements quite well. It is therefore only natural to find many MT2.0 studies on elastomers in the literature. To my best knowledge, the first published was in 2009 [161]. A three-branched specimen was designed, where the two vertical branches of the T were connected to the grips of a tensile machine, and the third, horizontal, gripped in a passive clamp to constrain Poisson's effect, thus providing a more heterogeneous strain field without the need for a biaxial machine. This paper is also the first time that the VFM was formalized for large deformations, introducing the principle of virtual work expressed in the reference coordinate system for ease of expansion of the virtual fields. A two-parameter Mooney model was successfully identified. The same year, another attempt was published by the same group, this time employing a biaxial test machine, increasing the heterogeneity of the deformation field [162]. [163] proposed a similar study but using different geometries of tensile tests. In [164], a cruciform specimen was used, but mounted on a uniaxial test machine, the lateral arms being passively clamped to the posts of the test machine, in the same spirit as for the three-branched specimen in [161]. An Ogden model was identified with the VFM, and complemented with Mullins effect and viscoelastic relaxation times. [165] also reports the use of a biaxial test specimen (cross-shaped) but this time, loaded in a biaxial machine and employing non-proportional load paths. A Mooney-Rivlin model was identified using FEMU and the shape of the specimen reviewed in an attempt to populate the strain invariant space more fully. A study published in 2020 [166] focuses on the effect of poor measurements in the context of the testing of skin specimens. To validate their approach, biaxial tests on silicon rubber cross specimens were performed. The biaxial loading was provided by a standard tensile testing machine on which a biaxial loading rig was mounted. Because of a combination of shadows of the grips, lost DIC data for large deformations and suboptimal speckling, some data points were lost. The authors claim that they can still use the VFM to obtain good quality identification but do not detail how they compensate for the missing data (interpolation? padding?) A similar study focused on the problem of missing data at the edges with the VFM [167].

The work presented in [32] stands out from the previous ones as it does not make use of an *a priori* model but instead, uses a statistics-based approach called Data-Driven Identification (DDI, see Section 1.4). A wide unfilled silicone rubber sheet specimen containing four holes of different diameters was loaded in tension and DDI provided an output in the form of a point cloud in the space formed by the strain energy density and the two first strain invariants. The question however is what to do with this data. One could either use this to develop an analytical model or formulate a finite element solver that directly use this information as input rather than an analytical expression. In the same vein, there have been a few studies using so-called 'PDE discovery' to formulate the model as part of the identification process through a catalogue of possible terms in the strain energy density [37, 168]. Both studies use a version of the VFM with local virtual fields expanded over a finite element mesh.

Combining deformation and thermal measurements to investigate the energy balance related to the complex behaviour of elastomers is an essential step in that community. A fist study on this was published in [169] using the three-branched specimen of [161], providing a rich database but also underlying the practical difficulties associated with this kind of experiment. The study by Charlès and Le Cam [170] is original in the sense that it uses heat sources to identify a Neo-Hookean model. First, the thermo-mechanical coupling (TMC) heat sources are directly identified on a biaxial sheet specimen from temperature measurements and inversion of the thermo-mechanical heat equation. The deformation field is also measured during the test using DIC and the TMC heat sources derived by the Neo-Hookean model from the deformation field predicted. The identification attempts to minimize the distance between the two heat source fields by updating the parameters of the Neo-Hookean model. This is a very elegant method though hard to adapt to other classes of materials with weaker TMCs.

The behaviour of elastomers at high strain rates has also been approached by MT2.0. Mates *et al.* [171] employed a standard split Hopkinson pressure bar (SHPB) setup but used DIC and FEMU to identify a Marlow strain energy potential model rather than the standard SHPB analysis. In [172], a 1D impact experiment is combined with the VFM to identify a set of tangent moduli at increasing preloads, finally describing an Ogden law for the tested silicon rubber. The field of acceleration was used as a load cell in the identification. In a follow-up paper [173], the same group showed how a 1D impact test could be combined with the VFM to identify an Ogden model at different strain rates, again using the acceleration field as a load cell. In [174], the same group improved on the process by using a load sensor at the loading end of the impact apparatus, thus providing more flexibility in the definition of the virtual fields. In the same spirit as in [172], and [98] for plasticity, a linear piecewise model was used to represent the stress-strain relationship. It should be noted that the DDI method proposed in [32] is also similar in principle (piecewise linear representation of the response), though the identification algorithm is different.

2.4.3 Foams and soft materials

[175] first used DIC and the VFM to identify the Poisson's ratio of standard and auxetic polyurethane foams at large deformation. The objective was to quantify the evolution of Poisson's ratio with compressive strain. A few years later, a series of two studies looked at the identification of the orthotropic stiffness components of PVC foams from a single test combining DIC and VFM. The first one [176] approached the optimization of the test, consisting of a cubic specimen mounted in a modified Arcan rig, by using the sensitivity to noise parameters from [28], in the same spirit as in [52]. In the follow-up article [177], the authors implemented the Digital Virtual Twin approach from [178, 179]. They found an optimal configuration but more interestingly, they were able to validate the DVT outputs experimentally, in the form of standard deviations arising from testing the same specimen multiple times. The result was that the predicted standard deviation arising from camera noise only accounted for about half the scatter on the identified stiffness components, the rest being due to mechanical loading uncertainties and other sources of error (uneven illumination, microvibrations, specular reflection etc.) Volume deformation from Digital Volume Correlation (DVC), a 3D extension of DIC, and the VFM were also used on foams or trabecular bone to obtain stiffness [180, 181].

The idea of using acceleration as a load cell in high rate testing [64] was also adapted to foams in [182, 183, 184, 185]. Here, the additional difficulty is that since the materials are highly compressible, the density changes significantly throughout the test. The authors have devised a way to update the density locally based on strain measurements to compensate for this effect. The same idea of using the acceleration as load information was published in [186], using data from [155] on a polymeric foam mimicking a scaffold for bioengineering applications. From this idea, the concept of the IBUS test was born [154].

Most of the MT2.0 activity on soft materials takes place in the biomedical community and this was decided outside of the scope of this review, but it is worth mentioning work in [187]. The authors used vibration shear loading at frequencies between 20 and 1,000 Hz. The VFM was used with the acceleration field providing the load information. Frequency-dependent properties of a very soft silicone rubber gel were successfully identified. It is also worth noting that the latest state of the art in synthetic image deformation (Digital Virtual Twin) was used to evaluate the performance of the technique.

2.5 Natural materials

2.5.1 Wood and wood-based products

This is another area where MT2.0 has been significantly studied, for the same reason as for composites (anisotropy), with the added difficulty of the presence of heterogeneities at an intermediate scale (growth rings), complicating the process. The first study that the present author is aware of dates back to 2002 [188]. The authors used a wood panel loaded in bending, with loading points determined through a procedure that maximizes the sensitivity of the displacements to each stiffness parameter. A viscoelastic orthotropic law was considered. Deflections were measured using a fringe projection technique, which were then compared to finite element simulated ones through a cost function to be minimized. A follow-up study was published in 2005 [189] though it did not bring much more to the state of the art than the first one. Additional work on panels, Medium Density Fibreboard (MDF) in this case [190], and clear wood [191] used deflectometry and the VFM but only considered elastic rather than viscoelastic properties. A series of work was also released that used the unnotched Iosipescu test, the grid method and the VFM to identify the in-plane orthotropic stiffness components of a pinewood tree species [192]. The methodology was then employed to assess the variability of the wood stiffness as a function of the position of the specimen within the log (top/bottom, pith/bark) [193]. Finally, an preliminary attempt to obtain early and late wood elastic properties separately was published in 2018 [194] but there is still much to do in this area.

2.5.2 Fibrous materials

An interesting study was published in 2008 [195] on crimped glass fibre wool, which is an insulating material. The crimping process results in a complex distribution of texture that can be characterized by a spatial field of orthotropy directions. The authors identified this field using image processing and where then able to obtain the material orthotropic stiffness components using FEMU. In [196], a drumhead specimen was designed to test the anisotropic stiffness properties of thin paper webs. The difficulty there was that the thin web could not sustain any significant compression, which led to the drumhead specimen. DIC and the VFM were used to identify anisotropic properties and it was checked that orthotropy was a good approximation for the material behaviour. Later, the spatial distribution of the modulus of a thin paper web was studied on a uniaxial tensile test with DIC [197]. The so-called Fourier-VFM [198] was used and compared with a segmented approach (*a priori* separation of different stiffness areas based on measured strains). The results were consistent between the two approaches. More interestingly, the results were similar when the specimens were tested several times in their elastic domain, including when specimens were removed from the grips, rotated and reloaded. For such complex fibrous materials, MT2.0 is invaluable as MT1.0 just provides a homogeneous response that fails to approach the complexity of the local behaviour which ultimately drives the onset of damage and failure.

2.6 Brittle materials

Because brittle materials are extremely difficult to test at high strain rates with the current state of the art (split Hopkinson pressure bar, SHPB), MT2.0 exploration for these materials has mostly concentrated on high rate testing. In a seminal paper published in 2012, Pierron and Forquin [199] used an inertial spalling test on cylindrical concrete specimens in conjunction with the grid method and the VFM to identify high rate stiffness and failure stress. It was shown that because of the difference between tensile and compressive modulus, originating from the presence of porosities, the standard so-called Novikov formula tended to overestimate the fracture stress [200]. The concept was later reused for more detailed analysis [201, 202]. The idea of this test configuration was pushed further to lead to the Image-Based Inertial Impact (IBII) test which first published application was on Tungsten Carbides [203]. This led to unprecedented quality of tensile test stiffness and failure stress at strain rates on the order of 1000 s^{-1}.

2.7 Thermo-mechanical identification

A particularly interesting situation occurs when specimens are submitted to both mechanical and thermal loads. Indeed, in that case, the measured strains are composed of both mechanical and thermal strains. The situation is analogue to the case of plasticity where thermal strains play the role of plastic strains except that there is no hardening. It is worth noting that without the presence of mechanical loads, thermal strains can lead to thermal stresses when they are constrained. In that case, the resulting stress state is self-balanced. To the best knowledge of the author, the first paper looking at this is [204], though only based on simulations. The test case is a three-point bending test submitted to a mechanical load and a constant uniform change of temperature ΔT. Using the VFM, with six manually defined virtual fields, they could identify both the six orthotropic stiffness components and the two coefficients of thermal expansion (CTE). It is worth noting that the resulting set of equations is not linear but no detail about the non-linear resolution is provided in the paper. A three-point bending test was also considered in [205] but for an elastically-isotropic GH4169 steel alloy submitted to increased temperatures. The article reports experimental data exclusively, at three temperatures: 300, 500 and 700°C. They used Integrated DIC (I-DIC) based on an analytical solution to the three-point bending test and assumed free thermal deformations. In practice, plastic deformation close to the central loading point was neglected as a purely elastic model was considered. Both elastic constants and CTE were identified. In [206], the

VFM was used to identify the coefficient of thermal expansion of multi-material assemblies under purely thermal loads. The stiffness components were supposed to be known. Special optimized virtual fields were derived though there is a flaw in the analysis and it would need to be revisited. Experimental data for an assembly of copper and brass are presented, as well as simulations for an electronic component. In [207], simultaneous temperature and deformation fields were performed to identify a thermo-mechanical model using FEMU. The initial thermoelastic coupling followed by plastic heat dissipation allowed for a plasticity model (Voce) and thermo-physical parameters (density, heat capacity and coefficient of thermal expansion) to be identified. This was however performed on a standard uniform uniaxial tensile test and would need to be extended to more complex configurations for full validation in an MT2.0 spirit. [208] also used a standard tensile test to demonstrate heat resistant grids to be used with the grid method but at the end of the article, they used the VFM to identify the steel elastic stiffnesses one the one side, and the CTE on the other.

It is interesting to note that there has not been any application using heterogeneous temperature maps with heterogeneous mechanical states, except in [121] but with a simple thermal field arising from a Gleeble machine. This is certainly an interesting path to follow to enrich tests for viscoelastic, viscoplastic and creep identification, to name but a few.

3 Uncertainty quantification, test design and standardization

3.1 Uncertainty quantification

One of the key issues in deploying MT2.0 is uncertainty quantification. Indeed, one of the downsides of MT2.0 compared to MT1.0 is the complexity of the measurement chain: image recording, image processing and inverse identification. This chain is highly non-linear and propagating uncertainty through it is not straightforward. Errors are generally classified in two categories: random and systematic. According to the most recent version (2008) of the Guide for Uncertainty Measurement [209], these are now referred to as Type A and Type B for a more general classification.

Type A errors (random) are generally assessed by repeating measurements and recording scatter. This gives a measure of the precision. The main source of Type A errors in MT2.0 is the grey level noise of the camera sensors which translates to a noise in displacement and strain once processed with DIC or the GM. The most common way to simulate the effect of this noise is to consider it as a white Gaussian distribution, independent copies of which are added to the displacements components. These distributions are added to exact finite element data and fed into the identification procedure (as in [38] for instance, but there are many others). The level of displacement noise can be obtained experimentally by recording several images of a stationary or rigidly displaced object. Sometimes, a white independent Gaussian noise is added directly to the strains [210] but this is less realistic as the strain components are not independent from one another since they derive from displacements. In fact, the same argument can also be used for independent noising of the displacements as all components derive from the same set of pixels for a given subset. However, these simplistic approaches are mostly used for sensitivity analysis rather than providing in-depth uncertainty quantification and in that case, these simplified procedures are admissible. Identification procedures can also be optimized to lead to the lowest sensitivity to random camera noise effects. This is the case for Bayesian approaches for instance [53]. In the context of the VFM, effort has also been devoted to minimizing the effects of random noise for linear [28] and non-linear [211] problems. A very useful recent review article analyses these issues systematically [22].

Type B errors are however more difficult to assess. In the context of DIC, one source of systematic error is the fact that camera sensors have a fixed number of pixels and as such, DIC acts as a low-pass spatial filter[1]. This can lead to underestimated peak deformations in high gradient zones for instance. Another source of systematic error can be linked to inappropriate modelling of the boundary conditions in FEMU, or the choice of an inadequate model to

[1]Limited temporal resolution can also act as a low-pass temporal filter

represent the material behaviour. In all these cases, it is highly unpractical to assess the uncertainty by changing the parameters experimentally (like buying higher resolution cameras until strain convergence is reached for instance). According to the GUM, mathematical models can be used to approach uncertainty quantification and in the present case, this is the only option available in practice. This requires the development of a simulator that can faithfully replicate the complete identification chain. This is akin to a Digital Virtual Twin (DVT) of the experiment and will be referred to as such in what follows.

The first effort in that direction was published in 2009 [212] when the authors used synthetic image deformation to simulate deformation fields in plasticity. However, their approach was not coupled with identification and since large strains were considered, the interpolation was not critical. In 2012, [178] proposed the first full identification simulator with the GM and VFM. Because elastic deformation was considered, a supersampling scheme was introduced to mitigate interpolation errors. One of the main objectives of this work was to optimize smoothing parameters and test configurations, using the final uncertainty as a cost function to minimize. This simulator was then extended to DIC [179] where the supersampling was also employed to deform the speckle pattern in the elastic range. This procedure has been used many times subsequently either to optimize processing parameters and/or to design test specimens (see [1] for the latter). A particularly interesting study in that context was published in [177]. The DVT was used to optimize both test configurations and smoothing parameters and then, an extensive experimental campaign was undertaken to obtain a distribution of stiffness values for each tested specimen by multiple re-testing. The final standard deviations of the experimental results were about twice as large as the simulated ones across all identified stiffness components. This is consistent with the fact that only camera noise was used as a source of error in the DVT, while in practice, other sources play a role (like micro-vibrations, illumination variations, mechanical fixture alignment). In fact, **Badaloni *et al.*** [213] tried to integrate more experimental errors and managed to have a more realistic simulation of the uncertainties, though on a very simple test configuration (uniaxial tension). This is certainly an area where progress has to be made to make more realistic predictions and the DVT is an invaluable tool for this. Finally, it should be noted that the nature of I-DIC [24] is such that the systematic error from the low-pass filtering features of DIC are naturally taken into account.

3.2 Test design

Test design is a key feature of MT2.0. Indeed, now that a statically determinate solution is no longer required, the design space for the test configuration is quite extensive. The definition of optimal test configurations for MT2.0 is still an open problem. This report will not detail the state of the art in this area since a review article on this was recently published in Strain [1]. A few key statements are just recalled here.

- Several strategies have been used in the literature to define such a test. The latest advanced methodology consists in employing the Digital Virtual Twin approach (as described above). This is the only way to take into account the effect of the systematic error arising from the low-pass filtering effect of DIC [179].

- The choice of the test configuration is clearly dependent on the constitutive model to be identified and therefore, test optimization should be performed at least for several categories of constitutive models (orthotropic elasticity, isotropic elasto-plasticity, anisotropic elasto-plasticity, hyperelasticity, viscoplasticity etc.).

- Since the signal to noise ratio of the strain measurement is a key influencer of the identification performances, scaling of the loads between different geometries is essential to reach meaningful conclusions in elasticity.

- The spatial resolution of the camera is another key factor and published research shows that aspect ratios of the specimen field of view matching that of the camera sensors systematically leads to better results.

Test design is certainly the area where research effort should now focus as DIC and inverse identification (including uncertainty quantification) have now reached a certain level of maturity.

3.3 Standardization

MT2.0 will have fully integrated the toolbox of engineers when it has found its way to new test standards. It is interesting to note that in the early ages of DIC and other full-field measurement techniques, there was the idea that such techniques could be standardized. This was the objective of the European FP5 SPOTS project (Standardisation Project for Optical Techniques of Strain measurement) [214]. However, the recommendations from this project were never adopted by the technical community working with DIC. One of the main drawbacks of the proposed approach was that the complexity of DIC was not considered as a bending test was proposed for validation. This ignored the problem of low-pass filtering of deformation fields by DIC and was not helpful to guide users towards robust measurements. The DIC community has gradually moved towards the understanding that the complexity and versatility of DIC was a major obstacle to any standard. By analogy, DIC to some extent matches the complexity of finite element modelling (FEM) and there is no standard on FEM. The way FEM has made its way into industry as a trusted tool is through a combination of users training and certification, and verification tests (based on analytical mechanical solutions). It is interesting to note that the DIC community, assembled in the International DIC Society (IDICS, https://idics.org/), is following the exact same route. The DIC Challenge run by IDICS and the Society for Experimental Mechanics (SEM) is aimed at verifying DIC codes; IDICS also runs training and certification courses, and has published a guide of good practice [15]. The fast uptake of DIC by the industrial sector is a witness that this approach is working in practice.

While standardizing DIC is now widely considered as a dead end, standardizing MT2.0 test methods is very much on the agenda. In this case, dedicated test configurations are coupled with DIC and inverse data processing in a single standard aimed at particular materials. At the moment, to the best knowledge of the present author, there is no such standard and it is high time that the testing community comes together to initiate pre-standardization work. This could be done through the umbrella of the Versailles Project for Advances Materials and Standards (VAMAS, www.vamas.org). A Technical Working Area (TWA) dedicated to MT2.0 is currently being considered that aims at hosting a number of pre-standardization initiatives. Initial projects will cover anisotropic plasticity, orthotropic stiffnesses of composites and possibly high strain rate testing of composites.

4 Conclusion

This review provides a concise overview of the current state of the art relating to Material Testing 2.0 as defined in [1]. The main conclusions that can be drawn from it are as follows.

- MT2.0 relies heavily on the use of full-field kinematic measurements[2] and inverse identification[3]. Both technologies are now reaching a level of maturity that allows them to be embedded in new mechanical test methods. The main limiting factor to deploy MT2.0 relates to training as generally, neither full-field measurements nor inverse identification courses are available at undergraduate nor even postgraduate level in mechanics curricula at universities.

- The application area that has seen the largest number of MT2.0 studies in undoubtedly metal plasticity[4]. Plastic anisotropy (in the context of sheet metal forming) and welds are some of the most active areas of research.

- MT2.0 on polymers seem under-represented compared to the importance of this material in engineering.

[2]Digital Image Correlation (DIC) is currently the dominant tool in this field

[3]The Virtual Fields Method (VFM) and Finite Element Model Updating (FEMU), including Integrated DIC, are currently the dominant techniques in use

[4]This report has consciously left out applications in biomedical materials and tissues testing where the assumptions and tools are generally rather specific and often not very relevant to engineering materials

- Some applications of MT2.0 seem ready for transfer and standardization, like the simultaneous identification of all orthotropic stiffnesses of composites, while significant research effort is necessary to tackle heterogeneous materials for instance.
- The general topic of the design of optimal (or even just suitable) MT2.0 test configurations is a critically under-researched area at which most of the effort should now be directed.
- Finally, pre-standardization research should be initiated to favour the emergence of new MT2.0 test methods that can significantly improve the efficiency of mechanical testing of materials.

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