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**LITERATURE REVIEW ON TENSILE TEST STANDARDS FOR METAL
ADDITIVE MANUFACTURING**

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Literature Review on Tensile Test Standards for Metal Additive Manufacturing

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ABSTRACT

The aim of this literature review is to investigate which existing test standards are being used for additively manufactured materials, and the applicability of these standards. For the purpose of this review only static tensile properties will be considered. The development of new standards will also be discussed.

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CONTENTS

1. INTRODUCTION	1
2. EXISTING STANDARDS	2
2.1 TENSILE TEST METHODS.....	2
2.2 TEST PIECE CONSIDERATIONS	4
2.3 SUMMARY	5
3. DEVELOPING NEW STANDARDS	6
4. CONCLUSIONS.....	7
5. REFERENCES	8

1. INTRODUCTION

Additive manufacturing (AM) encompasses a series of processes where an object is built layer by layer using a digital model. This is in contrast to traditional methods where material is removed by machining to create the part. The AM industry has grown rapidly in recent years, especially in sectors where it offers potentially significant cost savings and shortening of supply chains as parts can be manufactured on-site rather than delivered by suppliers.

The range of available materials for use in additive manufacturing is rapidly expanding and, while AM was initially used for prototype development, it is now commonly used to manufacture end-products of increasing complexity. Due to the differences in additive manufacturing compared to conventional manufacturing, the process for accessing product quality will be different.

For additive manufacturing processes, the product's fundamental properties are determined by [1]:

- Material type (polymer, metal, ceramic, composite)
- Fusion/bonding process (melting, curing, sintering etc.)
- Feedstock (liquid, powder, wire, filament, sheet etc.)
- How the material is shaped (type of machine, architecture etc.)

The process of successively adding material makes the properties of the materials in the part highly dependent on the machine type as well as processing and post processing parameters. Therefore any measured material properties need to be coupled to the specific type of machine and process parameters.

A layered approach may also cause directional dependence in the material properties. Therefore, the material properties of the part may also be dependent on the part orientation and position in the build space during processing. This can be used to designers' advantage, where process parameters can be manipulated to create gradient material properties that may be desired for a part.

Due to differences in additive manufacturing compared to conventional manufacturing, the process of assessing product quality will be different. Since AM technologies are still immature there is a lack of relevant standards, guidelines and recommendations for stakeholders to rely on. This makes certification and testing challenging and time consuming. For any given application there is not a clear method to help determine the applicability and validity of coupon testing to a specific type of component. It is currently unknown how well a coupon will represent a final part due to uncertainty around the reproducibility of the printing process.

The aim of this literature review is to investigate which existing test standards are being used for additively manufactured materials, and the applicability of these standards. For the purpose of this review only static tensile properties will be considered. The development of new standards will also be discussed.

2. EXISTING STANDARDS

2.1 TENSILE TEST METHODS

A wide range of mechanical property test method standards exist. As there are currently no equivalent standards that are specific to AM parts some of the existing standards have been considered acceptable for use, either in the current form or with guidance to adequately account for the characteristic of AM materials.

ASTM have produced a standard, ASTM F3122, which serves as a guide to existing standards or variations of existing standards that may be applicable to determine specific mechanical properties of materials made with an additive manufacturing process [2]. Further guidance is also provided in the NISTIR 8005 document [3]. The existing standards relevant to this review cover tension tests under various conditions and calculation of modulus and Poisson's ratio.

Tension Tests:

The procedures outlined in test methods ASTM E8/E8M [4], ASTM E21 [5], ASTM E1450 [6], ISO 6892-1 [7], ISO 6892-2 [8], ISO 6892-3 [9], and ISO 6892-4 [10] explain guidelines for tension testing under various conditions to determine a material's yield and tensile strength over a range of temperatures from elevated temperatures to cryogenic temperatures. ISO 6892-3 has replaced ISO 15579:2000 and ISO 6892-4 replaced ISO 19819:2004. All these standards are applicable to materials made additively with requirements for powder metallurgy materials that should cover AM specimens. Some test geometries e.g. sheet-, wire-, and rod-shaped specimens, may not be appropriate for AM, due to the difficulty in producing these geometries.

Modulus:

Tension tests, as described by Test Method ASTM E8/E8M, can be used to determine the Young's modulus, tangent modulus and chord modulus of metal-based AM structural materials. Test Method ASTM E111 [11] describes how to determine the elastic material property based on the tension test. This standard can also be used to determine the Young's modulus, tangent modulus and chord modulus using the stress-strain behaviour. It is limited to materials, temperatures, and stresses where creep is negligible. This standard defines the three moduli and provides guidance on number of trials, specimens, temperature etc including both high and low temperatures.

Poisson's ratio:

Poisson's ratio is the ratio of transverse strain to the corresponding axial strain and is an intrinsic material property. This ratio can be useful to further describe any anisotropic behaviour of additively produced bulk materials. Test Method E132 [12] describes the method to determine Poisson's ratio based on the results of a tension test on a rectangular specimen using extensometers. Specimens should be stress-relieved, isotropic and homogeneous. This is for room temperature only and post-processing is required.

There are many factors that may influence the reported tensile properties, including material anisotropy, method of material preparation, porosity, method of specimen preparation, testing environment, specimen alignment and gripping, testing speed, and testing temperature. The standard processing factors should be recorded, to the extent that they are known, according to ASTM F2971 [13] and the guidelines of the referenced standards.

Whilst evaluation of mechanical properties of many AM materials can be conducted using the guidelines developed for conventional materials with existing testing standards, the coordinate systems and nomenclature specific to conventional materials testing are not adequate to cover the full spectrum of parts that can be produced by metal AM. Test reports should include the location and orientation of parts within the build volume of the AM system used, as outlined in ISO/ASTM 52921 [14].

A literature search indicates that many researchers are using the existing standards such as ASTM E8 and ISO 6892-1 for testing AM parts.

Suryawanshi *et al.* [15] used ASTM E8/E8M-11 standard for the specimen dimensions of uniaxial tests. Samples were machined from a block of 316L stainless steel produced by selective laser melting (SLM) of powder. They used 2 different scan strategies ‘single melt’ and ‘checker board’ and testing showed differences between orientations with respect to build direction.

Karnati *et al.* [16] used ASTM-E8 for the ASTM sub-size 304L stainless steel specimens produced by SLM. They compared results to those from 2 in-house designed test geometries and saw differences in UTS and yield strength from all 3 geometries.

Mower and Long [16] used ASTM E8-09, producing dog-bone tensile samples of AlSi10Mg and Ti6Al4V by SLM in different orientations. They also produced stainless steel tensile specimens using direct metal laser sintering (DMLS). Tensile data from all three specimen types were compared to conventional materials and the elastic moduli were found to be similar between the conventional and AM materials, but there were noticeable differences in the yield stress for different build orientations and processing methods. The authors found that AlSi10Mg and Ti6Al4V were limited by inherent brittle mechanisms the resulted in strain-to-failure values of only 1-4%. Higher Ductility was demonstrated in the 316L steel samples with higher yield strength and strain hardening than in the wrought, annealed samples. In contrast, yielding of the 17-4PH steel occurred at lower values than the conventional material. Orientation effects were evident in each AM sample set.

Hrabe and Quinn [18] used tensile specimens that were approximately equal to the rectangular cross-section sub-size specimens of ASTM E8. By use of the orientation nomenclature from ASTM F2921 tensile specimens for all parts had XY orientation. This standard has now been replaced by ISO/ASTM 52921-13 [14] (also known as BS EN ISO/ASTM 52921:2016). The specimens were manufactured by selective electron beam melting (EBM) of Titanium alloy, Ti-6Al-4V. The samples were tested according to ASTM E8 to investigate the effect of distance from the build plate, but no significant differences were found. Three different size parts were also built, and tensile testing of samples cut from these parts showed that part size had a small influence on ultimate tensile strength and yield strength.

Jacob *et al.* [19] used ISO/ASTM 52921 for sample build and ASTM E8/E8M for measurement of tensile properties of stainless steel S17-4 produced by Powder bed fusion (PBF) to investigate the effects of powder recycling. Mechanical properties obtained from specimens fabricated using powder recycled up to 11 times were similar to the properties of specimens produced from virgin powder.

Sufiiarov *et al.* [20] looked at the effect of layer thickness and build direction on Inconel 718 alloy specimens made using SLM. Tests for mechanical properties were run according to ISO 6892-1 for specimen manufactured perpendicular and parallel to the build direction. Results established that

horizontally manufactured samples show higher strength properties and lower plasticity in comparison to vertical samples. A similar dependence of the mechanical properties on the position of the samples is confirmed in the ASTM F3055 [21] standard.

Hitzler *et al.* [22] investigated the anisotropic mechanical properties of SLM 316L Stainless Steel and AlSi10Mg. The authors used the flat specimen geometry detailed in the German Standard DIN 50125:2009-07. They used DIN EN ISO 6892-1:2016 for the testing procedure – this is the German version of ISO 6892-1. Although the authors specified two standards, the standard DIN 50125 has been withdrawn and is superseded by DIN EN ISO 6892-1. The orientation dependencies of AM and bulk samples were compared and the general rule of higher strength occurring in a parallel layer to the loading direction, in comparison with the perpendicular layer to loading scenario, was proven accurate. DIN 50125 was also used by Schultze *et al.* [23] for the specification of their test piece geometry - using shape B for producing tensile specimens of Ti-42Nb alloy produced by SLM, and by Guschlbauer *et al.* [24] for copper SEBM (selective electron beam melting) samples.

The EOS Whitepaper [25] on mechanical testing of direct metal laser sintering (DMLS) parts state that to be able to compare the mechanical properties of AM parts with metal parts produced by other processes such as casting, forging etc., standard procedures should be applied which are accepted and commonly used for metal parts in general. For tensile testing EOS used the international standard ISO 6892:1998-03 and the European/German standards DIN EN 10002-1:2001-12 and DIN 50125:2009-07 to define the sample geometry, speed of testing as well as the interpretation of results and requirements of the testing machine. Both DIN EN 10002-1:2001-12 and DIN 50125:2009-07 have now been withdrawn (replace by ISO 6892-1). The report compared round and flat samples, machined and unmachined and influence of build direction for maraging steel and Ti6Al4V.

Dzuga *et al.* [26] used the existing standard ASTM E8 to define the test geometry and testing regime for tensile testing of miniature Ti6Al4V samples produced using SLM and SEBM. The sample orientations used were consistent with that defined in a proposed ASTM standard ASTM WK49229 [27]. This standard will be discussed further in section 4.

2.2 TEST PIECE CONSIDERATIONS

Test specimens are vital in developing a broad data set and in providing confidence in the properties of the final part. A key aspect of many qualification regulations is that the properties of test specimens and test elements (representative of part features) must truly reflect the scatter in properties of the final part from all sources [28]. In addition to initial qualification specimens, test specimens may be included with each AM build. Their primary use is as a representation of the final part or part features which can be cut up and used to track variation in part properties whether between locations in the build volume or between builds.

In additive manufacturing it is known that properties are dependent on many factors. For instance, Hitzler *et al.* [22] found that the scan strategy influenced the material characteristics significantly and even simple precautions, such as limiting the irradiation pathways to avoid possible interactions between emerging particles with the laser beam, promote inherent directional dependencies. They showed that progression of the mechanical characteristics by altering the inclination between the loading and the layers differed and is highly material-dependent. Stainless steel exhibited its peak strength and maximum Young's modulus under a 45° offset between the layer and loading direction, whereas the aluminium–silicon alloy AlSi10Mg revealed the lowest strength in this instance.

The geometry of the AM part being built may affect its thermal history which could in turn affect its microstructure and mechanical properties [28]. As-built standard test coupons that have a different thermal history may therefore not be representative of the microstructure and properties of the final part. A witness specimen is a specimen built along with AM components from the same build cycle with the same feedstock, chamber environment, process parameters and post-process treatment [1]. According to ASTM standard F2971 [13] witness specimens for tension testing shall be machined from bulk deposition near net shape components and built in four orientations in accordance with ISO/ASTM 52921 [14]. The location of witness specimens within the build volume also needs to be reported. As a result of different geometry and variation during manufacturing, there is a lack of confidence in representing the properties of real AM components by the limited number of witness specimens [1].

At an ASTM/NIST workshop in 2016 it was suggested that current standardised destructive test methods may be inappropriate for metal AM materials as they typically assume material homogeneity, specific size and design of test specimens that may not be practical for AM materials [29]. The workshop attendees also agreed that witness coupons can be effective in documenting process variations during a build, but that the differences in specimen size, thermal history and local build parameters mean the witness sample are not necessarily representative of the actual components. The issue of similarity between the AM parts and test coupons is complex but needs to be understood and addressed as a high priority due to its potentially significant impact on the fidelity of AM process and parts qualification [29]. For powder bed systems it is recommended that test specimens should be included with each build to track variability between builds. The test specimens should be representative of the final part with microstructure and mechanical properties used to confirm this [28].

2.3 SUMMARY

From the literature reviewed it is clear that there can be a large variation in mechanical properties of materials, dependent on the processing parameters used. In some instances, properties such as Young's modulus, will be similar between AM samples and conventional samples, while large differences in yield behaviour is observed. One of the key aspects of testing AM samples is to understand how well the sample represents the AM part. Currently there is a lack of confidence in representing the properties of AM components by testing a limited number of samples.

It is evident that most existing mechanical test standards can be applied to AM specimens but with the following guidance [2], [3], [28]:

- Care must be taken in using flat plate or thin specimens since these samples may be difficult to build using AM and consequently test coupons may not be representative of the AM parts.
- Test reports should include the location and orientation of parts within the build volume of the AM system used, as outlined in ISO/ASTM 52921.
- Test methods with strict requirements for isotropy such as ASTM E1875 (Dynamic Young's modulus) may be difficult to apply if the AM process produces samples that are anisotropic.

3. DEVELOPING NEW STANDARDS

It is clear that although existing standards can be used for AM parts with guidance, currently available mechanical testing standards are not capable of addressing all of the requirements of testing for AM materials. The ASTM International Committee F42 on Additive Manufacturing Technologies and the International Organization for Standardization (ISO) TC261 Committee on Additive Manufacturing have started separately, and in some cases jointly, standard development to address this deficiency [30]. While ASTM standards exist and continue to evolve for documenting the various mechanical properties for additively manufactured materials, such standards are only in their infancy with ASTM F42. The intent is not to invent completely new standards, but rather develop guidelines based on existing standards.

The main, currently evolving, standard related to tensile testing of AM parts is ASTM WK49229, New Guide for Orientation and Location Dependence Mechanical Properties for Metal Additive Manufacturing [27]. This standard serves as a guideline for extending currently available standards for measuring mechanical properties of materials made by additive manufacturing. The title and scope are in draft form and are under development within the ASTM F42 Committee.

In 2016, America Makes and the American National Standards Institute (ANSI) launched the America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC). The AMSC was established to coordinate and accelerate the development of industry-wide AM standards and specifications consistent with stakeholder needs. The catalyst for the AMSC was the recognition that a number of standards developing organizations are engaged in standards-setting for various aspects of additive manufacturing, prompting the need for coordination to maintain a consistent, harmonized, and non-contradictory set of additive manufacturing standards. Key standards developing organisations include ASTM, SAE, ASME, SME, AWS, etc., and through AMSC these organisations can work alongside OEMs with the goal of facilitating joint standards development. The AMSC mission is not to develop standards, but to provide a roadmap that includes a gap analysis for standards and specifications and outline relevant published standards and specifications as well as those in development. This will minimise the amount of overlap activities across the various standardisation organizations. AMSC 18-001 is a preliminary final draft of this roadmap [31]. These activities are being viewed as a mechanism that can facilitate product qualification and certification. For example, aero engine parts could be certified by FAA while biomedical parts could be certified by FDA [30].

The AMSC have carried out gap analysis which has highlighted a need for research into measuring material properties of AM materials. Their recommendation is that standards need to be developed that identify the means to establish minimum mechanical properties (i.e. AM procedure qualification requirements) for metals made by a given AM system using a given set of AM parameters for a given AM build design [31]. If only typical values of properties exist large safety factors are required in the design process. If minimum properties can be guaranteed, smaller safety factors can be used. Defining a set of minimum properties for AM products is difficult because of the fact that properties are dependent on many process variables. Since the relationship between these variables and properties is not well understand, and as the method of qualifying minimum properties may be application dependent, developing a well-supported set of minimum properties is a challenge. Developing these standards will require generating data that either doesn't exist or is not in the public arena.

Currently, the only standards that contain minimum properties for AM parts are those from ASTM Committee F42 for specific metals produced by laser powder bed fusion: F2924, F3001, F3055 and F3056, covering Ti6Al4V and Nickel alloys. These do so by leaving the method of qualification up to an agreement between the purchaser and the supplier. Many other factors, not all of which are

currently known or understood, can interact in a way that creates highly complex processing conditions. To get test data that are valid for a given process, all process parameters must be fixed under controlled conditions, including post-build treatments. The resultant data are then only useful for that specific process. Standardising an optimised process therefore significantly lowers the amount of testing required to determine guaranteed mechanical properties, but this standardisation is likely to be machine-specific, at least in the near future [31]. Qualification requirements to establish minimum mechanical properties for AM parts, both homogeneous and deliberately inhomogeneous, need to be developed and AMSC have graded this as a high priority for metals.

Although the development of AM standards is being carried out by several standards organisations, this process is understandably quite lengthy. Some large companies cannot wait for the development of these standards and so they are creating their own standards, specific to their needs. This is the case with NASA and their program partners [32]. Each standard they create will be based on the MSFC standard MSFC-STD-3716 [33], written for mature AM technologies for an agreed family of materials. The materials testing is based on applicable standards such as ASTM E8/E8M for tensile testing.

Within the maritime industry DNV GL do not apply the traditional qualification and certification approach to AM manufactured products. Approval of AM processes and parts is currently dealt with on a case-by-case basis using a certification pathway which has three phases: - procedure qualification, approval and certification of materials/components [1].

For military aviation it was agreed at an MASAAG (Military Aircraft Structures Airworthiness Advisory Group) meeting that the manufacture of AM parts included new processes that introduced variability which needed to be understood, qualified and controlled for AM of airworthiness critical parts to be qualified and certified. For the potential benefits of this technology to be fully exploited, an approach to balancing risk and opportunity needed to be agreed. As part of the approval process, part validation is carried out where both the final part and the test specimens are tested to determine whether the part meets the specification [28]. The MASAAG recommended that existing, recognised standards (e.g. ASTM, ISO, BSI etc.) are used where applicable to inform the qualification and certification of AM components as this is one of the four pillars of airworthiness.

4. CONCLUSIONS

This review has highlighted that measuring the tensile material properties for AM products is difficult because properties are dependent on the type of process, the process parameters, the direction of the test sample relative to the build direction, the location on the build plate, the type of machine used for the build, and the geometry, among other factors.

Existing standards for tensile testing have been found to be adequate for AM produced materials with additional guidance to account for the characteristics of AM materials. Some guidelines have been produced by ASTM and these are the basis of the standard ASTM F3122.

As AM is now being used to manufacture increasingly complex products there is a strong need for more AM-specific standards. Developing these standards will require the generation of much more data for a wide range of systems, and a much greater understanding of the link between process variables and the material properties. This is seen as a high priority for AM metal products.

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