EASI-STRESS

EUROPEAN ACTIVITY FOR STANDARDISATION OF INDUSTRIAL RESIDUAL STRESS CHARACTERISATION

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EASI-STRESS

Deliverable Report:

D6.3 Report on residual stress characterisation, AM

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List of Abbreviations

AM	Additive Manufacturing
ASM	American Society for Metals
ASTM	American Society for Testing and Materials
CEN	European Committee for Standardization
ECSS	European Cooperation for Space Standardization
HDM	Hole Drilling Method
NDT	Non-destructive testing
PBF-L	Laser Powder Bed Fusion
RS	Residual Stress
YS	Yield strength
UTS	Ultimate Tensile Strength
TC	Technical Committee
TE	Total elongation
TS	Technical Specification
SEM	Scanning electron microscopy
EBSD	Electron backscatter diffraction
TC	Technical Comity
WG	Working Group
XRD	X-ray diffraction

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Executive Summary

The EASI-STRESS project will develop a platform for the industry to exploit advanced characterization techniques.

The purpose of this deliverable is to define and share a strategy for using residual stress characterization options for quality assessment of 3D printed metal components. It will be used as a basis for discussions with non-partner stakeholders. The work is organized in three parts:

1. Updating the partner common platform of scientific bibliography by studying publications that analyse residual stresses in additive manufacturing.
2. Summarize experiments and tests from EASI-STRESS to assess the quality of parts from AM produced by the EASI-STRESS consortium.
3. Investigate existing standards and specifications relating to AM seeking requirements and recommendations associated with residual stresses and destructive/non-destructive inspections.

The three parts will support the understanding of previous and current ongoing work and allow the definition of actions targeting the AM sectors. In addition, thanks to the involvement of individual consortium members in standardization bodies (TC CEN 138 and 438), a strategy to include residual stress measurements in European standards is defined.

EASI-STRESS will engage stakeholders in standardisation communities and promote the inclusion of residual stress measurement techniques in the standardisation for a listed below:

- CEN TC 138 (NDT), WG10 (Diffraction) has been initiated by EASI-STRESS and several consortium partners are engaged to develop a Technical Specification for residual stress measurement using synchrotron XRD where specific reference to AM will be made.
- CEN TC 438: Volum-e has the role of chairman of TC 438 and will work to propose the inclusion of residual stress measurement standards (and the TS from TC 138) as tools to assess stresses in AM.
- ISO TC 261: Since TC 438 is also the point of contact with ISO TC 261 AM, which publishes the standards for AM, residual stress NDT measurements will be brought into attention to the WG3 “Test methods” under TC ISO 261.
- ECSS: OHB will emphasize the relevance of NDT residual stress measurements in alignment with residual stress simulations for the prediction of residual stresses in the upcoming revision of the standard ECSS-Q-ST-70-80C.
- ASM: DTI will participate in the ASM Residual Stress Technical Committee with the purpose of exploiting synergies between Europe and US regarding the promotion of residual stress considerations in AM standards.

1. EASI-STRESS analysis of residual stresses measurement for AM quality assessment

State-of-the-art from literature

Additive manufacturing (AM) processes, especially laser powder bed fusion (PBF-L), generate many thermal variations in the parts. Coupled with the extremely fast cooling, this generates many residual stresses in the parts. These stresses can lead to distortion during the fabrication process and when the part is cut. They can also lead to cracking. To have a large vision on the works corresponding to the measurement of the residual stresses on the AM parts elaborated by PBF-L, a literature review was carried out.

The search for articles was performed from Science Direct and Google Scholar with the following descriptions:

- Residual stress PBF-L
- Residual stress additive manufacturing
- Residual stress assessment additive manufacturing
- X-ray + AM + LPBF + SLM
- Neutrons + AM + LPBF + SLM…

Firstly, we have looked at two reviews which give a state of the art on the development of residual stresses but also on the approach for their measurement in the parts by various techniques. These measurement techniques have the advantage of being non-destructive.

Most of the work on residual stresses has been done on a simple sample by X-ray diffraction or by neutron diffraction. In this paper, they show a global view of the different types of residual stresses with the corresponding scale to show the analytical techniques adapted for their measurements. Among them, the X-ray diffraction is one of the most used methods in the studies ([1], [2], [3]). However, in the Figure 1, it is clear that the depth of penetration is one of the main limitations. This is why more studies are focusing on neutron diffraction to measure the residual stresses deeper inside the parts.

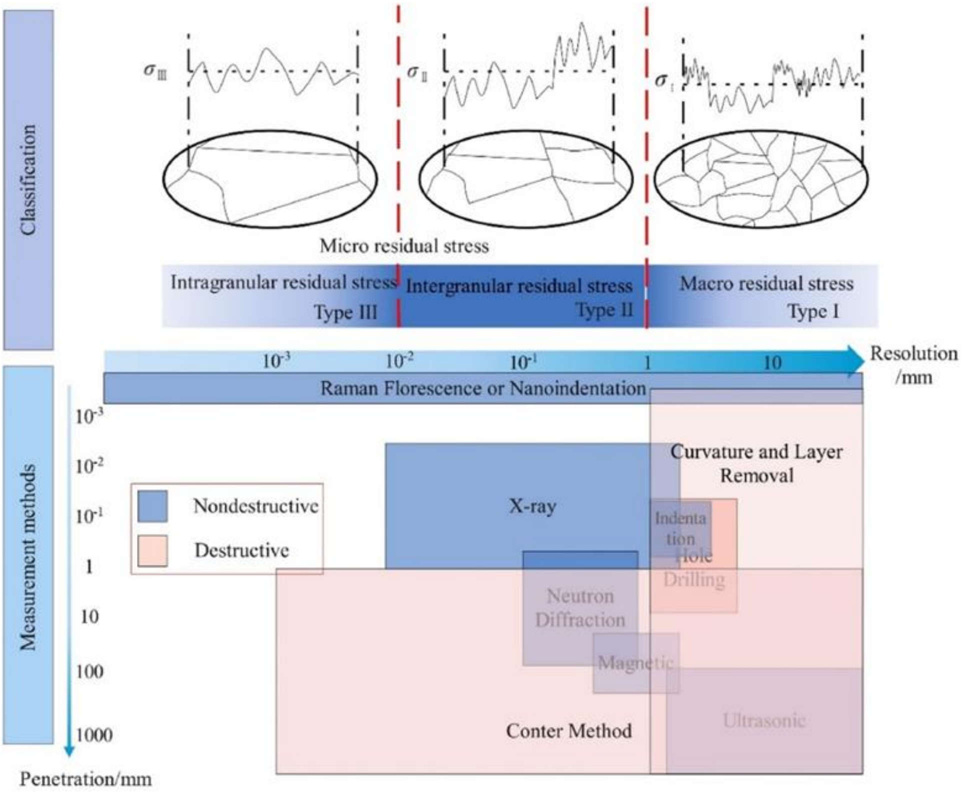


Figure 1: Global view of residual stress measurement methods with corresponding scales and analysis depths [4]

In a review [5], they present neutron diffraction as the most widely used non-destructive technique and also the one that is standardized to ISO 21432:2019. However, it explains that several parameters can influence the operation:

- Type of material
- The size of the sample
- The geometry of the part
- The depth of the test
- The amplitude of the expected stress gradient.

To go further in a study of Wu and al. [6], they used a digital image correlation analysis method to observe the deformations during manufacturing. They coupled this with neutron diffraction measurement. Prism and L-shaped samples were used (Figure 2 and Figure 3). The GOM non-contact strain measurement system was used to correlate the digital images (images before and after stress relaxation).

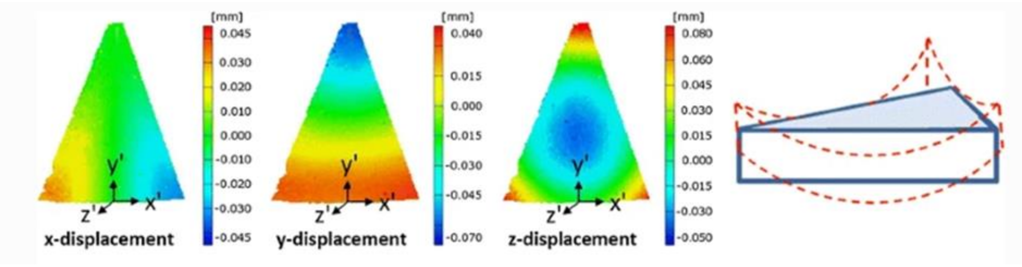


Figure 2: GOM analysis on a prism to observe the deformations generated during manufacturing

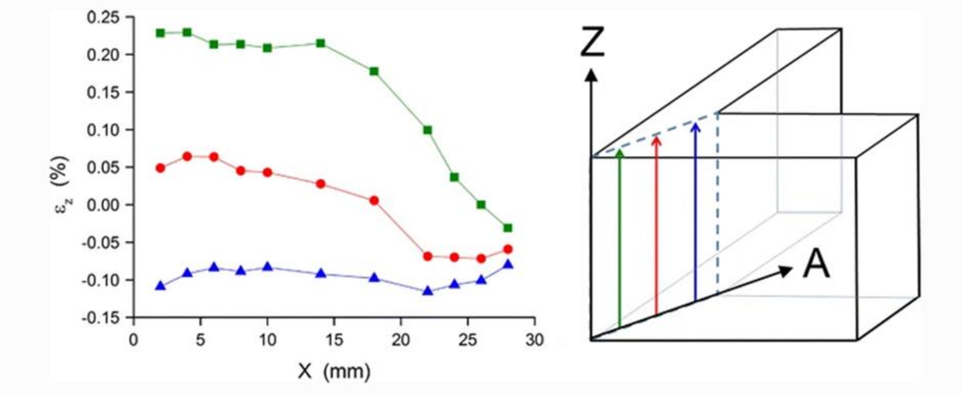
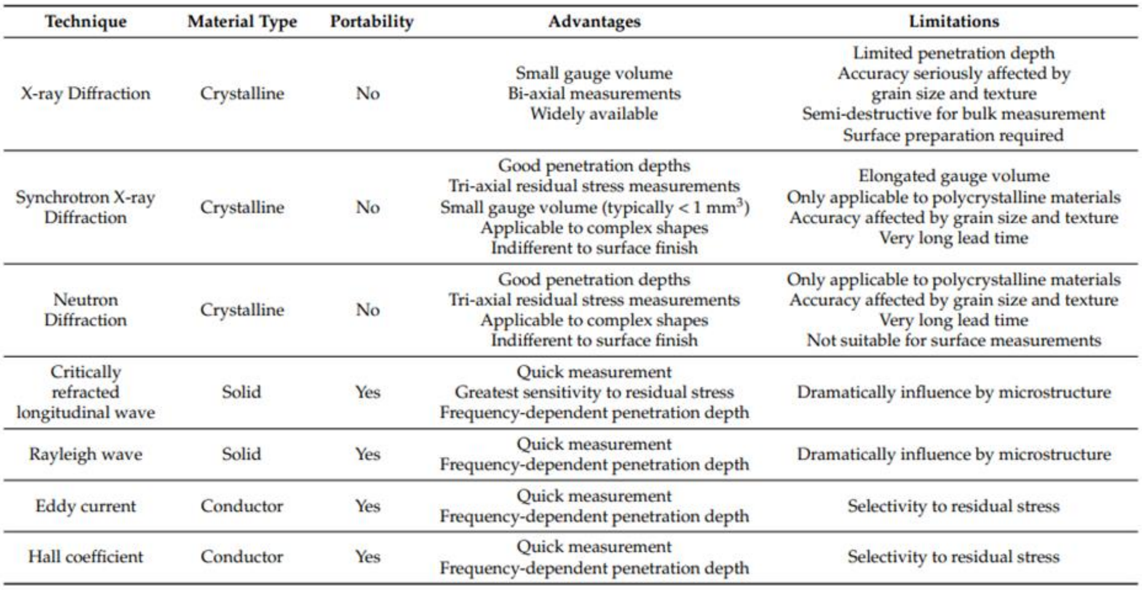


Figure 3: Measurement of residual stress along the angle on an L-shaped sample by neutron diffraction

However, the comparison between the Raman spectroscopy method and X-ray diffraction for the measurement of residual stresses on small cubes is carried on an AlSi10Mg alloy produced by LPBF in Marola's works [7]. To determine the compressive or tensile stresses in the parts, they observe the peak shifts of Si in the material with respect to standard Si. They concluded that the stresses determined by Raman spectroscopy are related to the micro stresses acting on the Si nanoprecipitates while those determined by DRX are related to the macro stresses acting on the Al matrix.

Although the largest number of studies are focused on X-ray diffraction and neutron diffraction to perform non-destructive testing on samples made by additive manufacturing. Some work focuses on ultrasonics for residual stress measurement [8], but they have a lot of difficulty to obtain repeatable results especially because of the quite complex microstructures obtained by AM. There are some techniques that can be interesting for industrial use such as eddy currents, but these require a conductive material. Moreover, the portability of this technique remains an important aspect in the integration of the device in a production line. Here is a synthesis of the different techniques with the corresponding advantages and disadvantages [8].



Technique	Material Type	Portability	Advantages	Limitations
X-ray Diffraction	Crystalline	No	Small gauge volume Bi-axial measurements Widely available	Limited penetration depth Accuracy seriously affected by grain size and texture Semi-destructive for bulk measurement Surface preparation required
Synchrotron X-ray Diffraction	Crystalline	No	Good penetration depths Tri-axial residual stress measurements Small gauge volume (typically < 1 mm^3) Applicable to complex shapes Indifferent to surface finish	Elongated gauge volume Only applicable to polycrystalline materials Accuracy affected by grain size and texture Very long lead time
Neutron Diffraction	Crystalline	No	Good penetration depths Tri-axial residual stress measurements Applicable to complex shapes Indifferent to surface finish	Only applicable to polycrystalline materials Accuracy affected by grain size and texture Very long lead time Not suitable for surface measurements
Critically refracted longitudinal wave	Solid	Yes	Quick measurement Greatest sensitivity to residual stress Frequency-dependent penetration depth	Dramatically influence by microstructure
Rayleigh wave	Solid	Yes	Quick measurement Frequency-dependent penetration depth	Dramatically influence by microstructure
Eddy current	Conductor	Yes	Quick measurement Frequency-dependent penetration depth	Selectivity to residual stress
Hall coefficient	Conductor	Yes	Quick measurement Frequency-dependent penetration depth	Selectivity to residual stress

Figure 4: Different Non-Destructive Evaluation (NDE) uses to measure residual stresses of metallic components in Aircraft engines [8]

A review of the use of ultrasound to measure residual stresses in parts elaborated by additive manufacturing [9] showed that these are promising techniques but there are still many barriers to overcome for wider use:

- Complexity of the parts resulting from AM (works only on simple geometries).
- Need for a reference sound signature: no data on the impact of microstructures, stresses, or changes in properties responsible for changes in sound signals.

For destructive testing, the Hole Drilling Method (HDM) and the contour method is the most widely used technique ([10], [11], [12]) to determine the residual stresses created during the manufacturing process. Moreover, to predict the distortion of parts in AM, the HDM method is coupled with simulation software. In Ma's works [13], they used arches fabricated by LPBF to understand how residual stresses behave in the different sections (pillars, thin curved sections, overhangs) and how this may affect the final distortions. They relied on ANSYS® and Simufact® simulation software (Figure 5). The arches were cut to measure the deformed angles with Alicona® (or similar) optical microscope, and the resistive stresses were measured using the Hole Drilling Method (HDM) in accordance with ASTM E837-20.

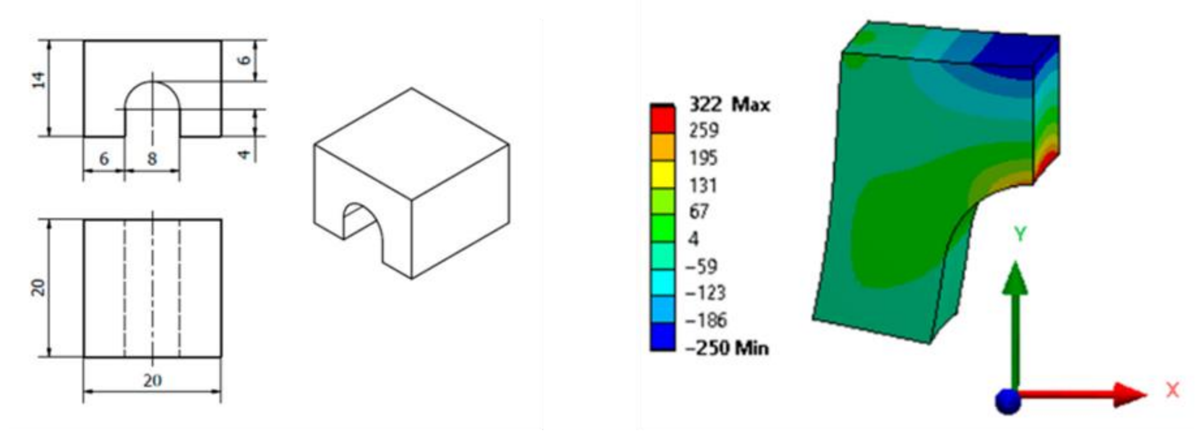


Figure 5: Bridge geometry with these dimensions in mm and normal stress distribution on the cut bridges calculated with ANSYS in MPa

Currently, most of the work is focused on the prediction of residual stresses to avoid deformations and cracks on complex parts. There are also many studies on the integration of thermal phenomena to improve the simulations. Moreover, due to the complex microstructure of the parts made in LPBF, it is complicated to define reference values that allow a better reliability of the data.

In order to predict and measure deformations due to residual stresses, it is important to develop accurate analysis methods that can be adapted to all types of geometries for parts made by additive manufacturing. In this perspective, the EASI Stress project has been established to evaluate the reliability of different measurement methods of residual stresses for AM parts.

Experience from EASI-STRESS on AM

This section is to show our approach to determine the residual stresses on well-defined types of parts (cantilever, arches...).

In EASI-STRESS, we have developed a methodology to minimize the residual stresses present in additive manufacturing compounds, that is mainly the deviatoric stresses [14]-[16], without compromising the mechanical properties, nor the microstructure.

This methodology is developed in three steps:

1. Selection of the stress relief treatment temperature range

In a first step, it should be defined by the material adequate ranges of temperature for the stress relief. A stress relief heat treatment is considered to be a heat treatment that reduces the internal stress state, without the intention of causing any phase changes, but recrystallization could take place [17]. Thus, we can select this temperature ranges from literature, thermodynamic calculations and/or empirical tests.

It is considered important always to verify the resulting microstructure after the stress relief treatment to assess with the as built one and to confirm that microstructural changes are minimum. The recommended metallographic characterization that has been followed at EASI-Stress comprises optical and scanning electron microscopy (SEM), electron backscatter diffraction (EBSD), X-ray diffraction, and hardness mapping.

Example of 316L

For additive manufactured 316L Stainless Steel in Laser Powder Bed Fusion (PBF-L) it has been reported in literature that no phase transformation occurs below 700 ºC (up to 400 hours study). When LPBF SS316L is submitted at 700 ºC carbides and Mo-rich phases can be formed, although at times lower than 20h no phase formation has been identified. However, at 800ºC phase formation occurs in half an hour [18],[19]. For this reason, the temperature range to study stress relief annealing was set between 600 – 700 ºC.

2. Distortion evaluation

Distortion is related to the tensile state of the sample [20]-[23]. This is a key point in additive manufacturing to guarantee and certify the final dimensions of the part, especially when the sample is removed from the build plate.

To evaluate the efficiency of different heat treatments on stress relief, distortion of sister samples submitted under different treatments have been measured and compared with the as-built state. To do so, a well-known a double cantilever geometry has been proposed. This geometry consists of a central pilar and two extended horizontal arms. Figure 6 shows the proposed geometry used at EASI-Stress. While the central pilar remains attached at the build plate, samples arms are removed from it by electron discharge machining (EDM) do not modify the original stress state of the printing manufacturing process. Then, the extended arm constraint is removed, and arms are free to displace in the z-direction. Thus, the distortion in this direction is measured with a profilometer at both sides (A and B caption at Figure 6) to have a better averaged value.

Figure 6: Picture of proposed Cantilever structure to measure distortion with 2 arms A y B. The EDM removal from the build plate is sketched by a red dashed line

Figure 7 gathers the distortion results of the different heat treatments studied for 316L steel printed in Laser Powder Bed Fusion (LPBF). It shows that the most effective treatment was at 700ºC for 2 hours, where the distortion measured in the as-built sample is reduced by half, indicating the potential efficiency of the treatment.

Sample	Location	Initial Value	Final value	Z-displacement
As-Build	A	8.01	9.51	1.50
	B	7.98	9.62	1.64
700 ºC/2 h	A	7.98	8.71	0.73
	B	7.97	8.61	0.64
700 ºC/1/2 h	A	8.13	9.56	1.43
	B	7.96	9.68	1.72
650 ºC/2h	A	7.99	9.51	1.52
	B	7.97	9.46	1.49
600 ºC/2h	A	7.94	9.43	1.49
	B	8.00	9.47	1.47

Figure 7: Measurements of the z-distortion of 316L LPBF printed material after different heat treatments and as-built condition. The most effective treatment was at 700ºC for 2 hours (red).

All above heat treatments were performed under a protective atmosphere of Argon to avoid any possible oxidation of the steel.

3. Tensile properties

Finally, the effect of the stress relief heat treatment on tensile properties was analyzed. Besides the reduction in distortion, the effectiveness of the stress relief can be evaluated with the tensile properties. The procedure followed was to include tensile samples on the same heat treatment cycle as the cantilevers so the differences in the distortion can be correlated with the mechanical properties. Tensile specimens have been manufactured following the standard ASTM E8 with subsize rectangular geometry

A good stress relief treatment stands for an increment in the total elongation of the material with a consequent reduction of the yield strength according to the Bauschinger effect.

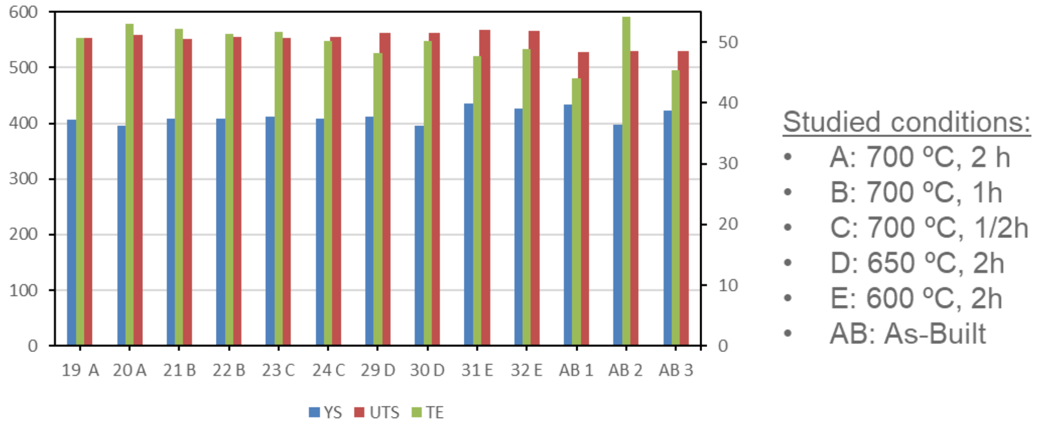


Figure 8: Tensile properties of 316L LPBF printed material after different heat treatments and as-built condition.

The tensile results are compiled at Figure 8. The yield strength (YS) is represented with blue bars, the ultimate tensile strength (UTS) is represented in red and total elongation (TE) in green. Heat treatment “A” (700 ºC for 2h) gave the best results in distortion reduction. This is the most severe treatment in terms of temperature and time-tested and the less severe one is “E” (600 ºC, 2h) at the right part of Figure 8, next to the as-built tested samples (AB).

Regarding the yield strength, from the as-built and less severe heat treatments to the higher in temperature and time (A), YS-tendency shows a decreasing behaviour while the TE increases. This is exactly what it was expected. Only one coupon (AB 2 sample) shows a very different behaviour that can probably be an anomalous specimen or measurement.

On the contrary, based on the Bauschinger effect UTS should remain constant. However, this is not the case, and for all the studied heat treatments, UTS has increased. Two hypotheses were proposed to explain this phenomenon: on the one side, the stress state of additive manufacturing parts that has been measured at the EASI-Stress is not necessarily homogeneous (Figure 9), and thus, there are some locations of the sample that are highly stressed than others, leading this premature failure and when a stress relief is applied, the stress state is a homogenized. On the other side, it is possible that only local microstructural changes and relaxations occur, and this is the driven phenomena to increase the material strength. In any case, heat treatment is shown to be beneficial in improving the properties of the as-built material. And it could even have a greater impact on dynamic or final properties such as fatigue, corrosion cracking, etc... which were beyond the scope of this project.

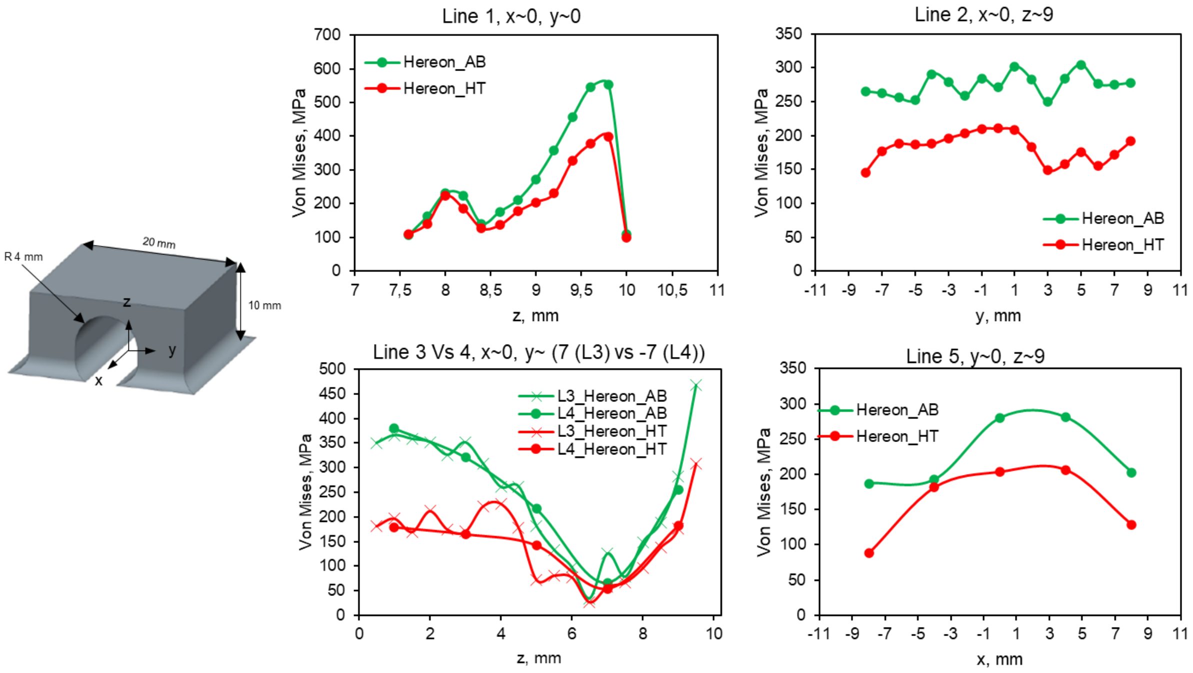


Figure 9: Equivalent Von Mises stresses measured at EASI-Stress Additive Manufacturing benchmark samples by X-ray synchrotron diffraction in As-Built (AB) and Heat treated (HT) samples. Stresses have been measured at different scanning directions, defined by the coordinate system and heat treatment was at 700 ºC for 3 hours.

2. Residual stress in AM standards

Requirements in business-to-business customer-supplier relationships often rest on (third-party) approval according to standards from ISO (global), EN (European), ASME (American) or ECSS (space) – plus national norms from, e.g., DIN (DE) or BSI (UK).

As an example, for railway tracks, it is specified in the current standard that the residual stresses in a given area of the component should be less than 200 MPa[1]. It is, however, not specified how this value should be measured.

While the previous section document the importance of managing residual stresses in order to produce non-distorted AM parts, residual stress limits and assessment is currently not significantly featured in the standards. This section investigate the current considerations regarding residual stress and non-destructive testing in the present standards for AM.

Inventory of AM standards

The main priorities of the Technical Comity CEN 438 are to provide a complete set of European standards on processes, **test procedures**, quality parameters, supply agreements, fundamentals and vocabulary based, as far as possible on international standardization work. The aim is to apply the Vienna Agreement with **ISO/TC 261** "Additive Manufacturing" (DIN) to ensure consistency and

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[1] EN 13674-1:2011+A1:2017 "Railway applications. Track. Rail Vignole railway rails 46 kg/m and above"

harmonization. Furthermore, the TC gets the objectives to strengthen the link between European Research programs and standardization in additive manufacturing.

AM standards today are written by TC ISO 261 and ASTM F42. These two committees have signed a PSDO collaboration agreement since 2012. Thus, thanks to the Vienna agreement between CEN and ISO, these ISO/ASTM double logo standards become CEN/ISO/ASTM triple logo standards if they comply with European regulations.

To date (December 2022), of the 25 existing AM ISO standards have been published, 23 of them are EN. In addition, on the 33 draft standards are under development, 30 follow the Vienna agreement and will become EN standards.

Review of ISO/ASTM standards relating to residual stress measurements

We have compiled in the following table all the AM standards in which mention is made of residual stresses:

Reference and Title	Mention of Residual Stress	Comment
ISO/ASTM 52901:2017; Additive manufacturing — General principles — Requirements for purchased AM parts	4.4.1 - General The most important part characteristics from the customer view shall be identified, particularly those related to dimensional accuracy, defects, mechanical properties, **residual stress**, or chemical composition.	Just informative, nothing else in the text
ISO/ASTM 52911-1;2019 Additive manufacturing — Design — Part 1: Laser-based powder bed fusion of metals	5.2 - Size of the parts The size of the parts is not only limited by the working area/working volume of the PBF-machine. Also, the occurrence of cracks and deformation due **to residual stresses** can limit the maximum part size.	Finding of the impact of RS
ISO/ASTM 52911-1;2019 Additive manufacturing — Design — Part 1: Laser-based powder bed fusion of metals	6.7.6.3 - Reducing thermally induced **residual stress** During PBF-LB/M, the layer-wise build-up method combined with lateral shrinkage as each individual layer cools often generates significant residual stresses in the finished part. Heat treatment shall be used for stress relief before removing the part from the platform.	Requirement to remove residual stress via heat treatment
ISO/ASTM 52911-2, Fabrication additive - Conception - Part 2: Powder bed fusion of polymers	5.4 - Limitations to be considered in regard to the PBF process Shrinkage, residual stress and deformation can occur due to local temperature differences… ...Consideration shall be given to deviations from form, dimensional and positional tolerances of parts. A machining allowance shall therefore be provided for post-production finishing. Specified geometric tolerances can be achieved by precision post-processing...	RS defined as disadvantage because it creates deformation that shall be taken in consideration and limited before and after production.

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ISO/ASTM 52911-3, Additive manufacturing — Design — Part 3: PBF-EB of metallic materials	5.2 - Size of the parts The size of the parts is not only limited by the working area/working volume of the PBF-machine. Also, the occurrence of cracks and deformation due to residual stresses can limit the maximum part size. Another important practical factor that can limit the maximum part size is the cost of production having a direct relation to the size and volume of the part.	Finding of the impact of RS
ISO/ASTM 52910, Additive manufacturing — Design — Requirements, guidelines and recommendations	6.6.10 - Physical considerations To be suitable for AM, the part shall be designed such that all thin areas of the part are thick enough to accommodate the minimum thickness requirements of the target AM machine as well as pre-processing software such as slicers. The designer shall also consider the physical orientation of the part... ... Consideration of the effects of **residual stresses** and shrinkage can be important when determining part orientation as well. The part should be arranged in the software in the desired manufacturing orientation for maximum ... ... The physical mass of the part being manufactured shall also be considered, depending upon the selected manufacturing process, to ensure that gravity or **other external** forces do not cause the manufacturing process to fail.	Information for designer
ISO/ASTM 52912;2020 Additive manufacturing — Design — Functionally graded additive manufacturing	6.1 - General By simplifying the assembly, of complex parts using dynamic gradients, some of the known disadvantages of traditional composites can be avoided such as lowering the in-plane and transverse stresses at critical locations, **improving residual stress**	Just informative, nothing else in the text

	distribution, enhancing breakage resistance and thermal properties, attaining higher fracture toughness, and reducing stress intensity...	
ISO/ASTM 52920, Additive manufacturing - Qualification principles - Requirements for industrial additive manufacturing processes and production sites ISO/ASTM 52930; Additive manufacturing — Qualification principles — Requirements for industrial additive manufacturing processes and production sites	4.5 1)b)ii) Process parameter incorrect setting of process parameters can lead to part failures: cracking, delamination, high residual stresses, poor surface finish, increased part porosity, lack of fusion, polymerisation, bonding or sintering	Just informative, nothing else in the text
	6.4.2.1 - Critical process input and output variables Control of the following variables are deemed to have an effect on the quality of the output. For product performance qualification, the variables which have been determined in OQ to have an effect on the quality of the output shall be monitored and controlled using appropriate procedures and frequency determined and documented by the AM machine user. For PBF-LB processes, the following variables are deemed to have such effect: ... 4. -excessive residual stresses, leading to warpage, cracking or delamination;	

Review of ECSS standards relating to residual stress measurements

The European Cooperation for Space Standardization (in short: ECSS) is an initiative established to develop a single, coherent set of user-friendly standards for use in all European space activities. ECSS is a cooperative effort of the European Space Agency, national space agencies and European industry associations for the purpose of developing and maintaining these standards.
ECSS standards are intended to be applied for the management, engineering, product assurance and sustainability in space projects and applications. In general, the ECSS standards define what shall be accomplished, rather than in terms of how to organize and perform the necessary work. This allows existing organizational structures and methods to be applied where they are effective, and for the structures and methods to evolve as necessary without rewriting the standards.
In 2021, a dedicated ECSS standard was the product assurance for metal parts made by Additive Manufacturing was published. The ECSS-Q-ST-70-80C covers the main aspects of metallic powder bed fusion technologies regarding processing and quality assurance requirements for space applications. The standard refers to several other standards related to non-destructive testing, fatigue testing or fracture control.

We have compiled in the following table the most relevant ECSS standards regarding additively manufactured parts in which mention is made of residual stresses.

Reference and Title	Mention of Residual Stress	Comment
ECSS-Q-ST-70-80, Space product assurance, Processing and quality assurance requirements for metallic powder bed fusion technologies for space applications	12.5.3 Fatigue testing 12.5.3.1 Overview Parts produced with Laser Powder Bed Fusion processes generally exhibit a rather high surface roughness, have **residual stresses**, and a varying microstructure throughout the build height. These features are known to have an effect on the fatigue performance.	Just informative (for fatigue tests)
	Annex B (normative) Additive Manufacturing Procedure (AMP) – DRD B.2 Expected response B.2.1 Scope and content ECSS-Q-ST-70-80_1480205 The AMP shall contain the following information: Type of recoater (blade, material of blade, roller, or other) NOTE 2 to item 9 (b): The baseplate serves several purposes. One of them is to provide stiffness to counteract bending forces due to the accumulation of **residual stresses** during the build process. High-strength materials and parts with high-volume cross sections may require thicker plates than materials with lower strength or filigree designs.	Just informative

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ECSS-Q-ST-70-15, Space product assurance, Non-destructive testing	N/A	No statement on stress measurements or residual stresses
ECSS-E-ST-32-01, Space engineering, Fracture control	3.2 Terms specific to the present standard 3.2.31 **residual stress** stress that remains in the structure, owing to processing, fabrication, assembly or prior loading	Definition
	7.2.3 Derivation of stresses for the critical location ECSS-E-ST-32-01_0810071 b. The stresses shall be derived for the worst credible combination of all influencing aspects NOTE For example, influencing aspects to be considered include: geometrical discontinuities and imperfections, manufacturing defects, **residual stresses**	Just informative
	8.3.2 Safe life analysis of welds ECSS-E-ST-32-01_0810131 e. Any **residual stresses**, both in the weld and in the heat-affected zone, shall be used in the safe life analysis.	Requirement to consider RS in safe life analysis of welds
ECSS-Q-ST-70-71, Space product assurance, Materials, processes and their data selection	4.2 Material requirements 4.2.1 General requirements a. Design stresses shall include all **residual stresses** including those coming from manufacturing and assembly processes.	Just informative

	4.2 Material requirements 4.2.11 Adhesives, coatings, varnishes h. Applications of thick coatings that can result in damage to the coated items shall be evaluated by testing. NOTE Resulting damage can be for example: high **residual stresses**, high temperatures during cure.	Just informative
	4.2 Material requirements 4.2.15 Potting compounds, sealants, foams e. The supplier shall assess the need of using pre-coating to ensure proper adhesion between the part and the potting compound or sealant and reduce **residual stresses** created during curing.	Just informative
	4.2 Material requirements 4.2.18 Thermoplastics j. Thermoplastics that retain **residual stresses** after processing shall be subject to an approved thermal stress-relief process.	Just informative
ECSS-Q-ST-70-45C, Space product assurance, Materials, processes and their data selection	5.4 Fatigue test 5.4.1 Force controlled constant amplitude axial fatigue test Axial load fatigue testing of threaded fasteners shall be carried out in conformance with clause “Fatigue test” of ECSS-Q-ST-70-46. NOTE Fatigue strength of welded components is typically influenced by weld **residual stress**. For this reason, fatigue testing of weld coupons is not representative of the effects of weld **residual stress** on the fatigue strength of real components.	Just informative (for fatigue tests)

3. Strategy for including residual stress measurement in AM standards

It is the ambition of the EASI-STRESS project to influence selected standardisation committees so that the following 3 levels are being considered or directly integrated into the future standards:

I. Mention of residual stresses as a parameter of relevance in the standards

II. Mention of NDT measurement of residual stresses as a possibility

III. Recommendation/requirement to employ residual stress measurement in qualification

From our survey of existing standards, it is clear that residual stresses are being rarely mentioned.

The strategy for EASI-STRESS to engage with the standardization community to change the situation on different levels is listed below:

CEN TC 138 (Non-destructive testing), WG10 (Diffraction) – Level III engagement

EASI-STRESS has initiated this Working Group in Task 6.1 and will lead the activity to develop a Technical Specification for residual stress measurement using synchrotron XRD. EASI-STRESS direct participants include DTI (DK), Danish Standards (DK), CETIM (FRA), Rolls-Royce (UK) and EK (HUN). The TS should specify Additive Manufacturing as a particular relevant application area for the TS.

The work in WG10 will also include the potential to add comments to the existing standards EN 15305:2008 (Non-destructive Testing - Test Method for Residual Stress analysis by X-ray Diffraction) and ISO 21432:2019 (Non-destructive testing - Standard test method for determining residual stresses by neutron diffraction). Again, via WG10, EASI-STRESS should comment that these measurement standards are applicable also to AM components as a quality control tool that may be mentioned next time the standards are revised.

Finally, the WG10 group should strengthen its formal connection (liaisons) with the CEN TC 438 AM.

CEN TC 438 (Additive Manufacturing) – Level III engagement

EASI-STRESS partner Volum-e has the role of chairman of TC 438 and will work to propose the inclusion of EN 15305:2008 (Non-destructive Testing –Test Method for Residual Stress analysis by X-ray Diffraction), ISO 21432:2019 (Non-destructive testing —Standard test method for determining residual stresses by neutron diffraction) and/or the new TS from CEN TC 138 WG10 as a tool to assess stresses in AM.

ISO TC 261 (Additive Manufacturing) – Level I engagement

CEN TC 438 is the historical and functional point of contact with ISO TC 261 AM which publishes the standards for AM. It will therefore be natural that the projects of WG10 of TC 138 which will touch on AM should work in conjunction with 438. If an NDT standard is specific to AM, it will be written within TC ISO 261 WG3 Test Method.

Relations with ECSS (Space sector) – Level II engagement

EASI-STRESS partner OHB and Volum-e was involved in the development of the ECSS standard ECSS-Q-ST-70-80C on Additive Manufacturing published in 2021. The relevance of AM for the space sector is growing where EASI-STRESS partners OHB and Volum-e are actively involved. (Non-destructive) testing provides essential tools for AM process qualification and AM part verification.

There is potential for the space-AM area to be one of the drivers for the inclusion of residual stress measurements as quality assessment method. For a revision of standard ECSS-Q-ST-70-80C within the next years, EASI-STRESS partner OHB will emphasize the relevance of NDT residual stress measurements in alignment with residual stress simulations for the prediction of residual stresses.

Relations with ASM (US) – Level II engagement

This is not the primary focus of EASI-STRESS, but DTI will participate in the ASM Residual Stress Technical Committee[2] which has an Industry Standards subcommittee that works together with representatives from standards organizations to create and update useful standards related to residual stresses. DTI is registered as participants in this group and will comment on the relevance of NDT residual stress measurement in relation to the development of AM standards.

4. Conclusions

Distortion driven by residual stresses is a major concern in metal additive manufacturing, but this is currently not being reflected in the standards for production or measurement. EASI-STRESS will engage stakeholders in standardisation communities and promote the inclusion of residual stress measurement techniques in the formulation of new standards for AM and for future revisions of existing standards.

Specifically, the following strategies have been devised:

- CEN TC 138 (NDT), WG10 (Diffraction) has been initiated by EASI-STRESS and several consortium partners are engaged to develop a Technical Specification for residual stress measurement using synchrotron XRD where specific reference to AM will be made.
- CEN TC 438: Volum-e has the role of chairman of TC 438 and will work to propose the inclusion of residual stress measurement standards (and the TS from TC 138) as tools to assess stresses in AM.
- ISO TC 261: Since TC 438 is also the point of contact with ISO TC 261 AM, which drafts the standards for AM, residual stress NDT measurements will be brought into attention to the WG3 “Test methods” under TC ISO 261.
- ECSS: OHB will emphasize the relevance of NDT residual stress measurements in alignment with residual stress simulations for the prediction of residual stresses in the upcoming revision of the standard ECSS-Q-ST-70-80C.
- ASM: DTI will participate in the ASM Residual Stress Technical Committee with the purpose of exploiting synergies between Europe and US regarding the promotion of residual stress considerations in AM standards.

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[2] https://www.asminternational.org/en/residual-stress-technical-committee

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