**EMPIR Call 2020 – Fundamental, Industry and Normative**

Selected Research Topic number: **SRT-i21**
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# Title: Metrology of diffraction-based residual stress analysis in additively manufactured materials and components

## Abstract

The additive manufacturing (AM) market of metal parts is predicted to grow by 25 % with a value of 4.6 B€ by 2030. Metrological challenges in the qualification of safety-relevant components severely hamper the use of additive manufacturing (AM) in European industry. Current standards for non-destructive (diffraction-based) residual stress (RS) analysis are not adequate for AM. Nonetheless, RS represents the most dangerous unknown in component life assessment; it is often blamed for early failure. The reliable and reproducible determination of RS would represent a breakthrough in safe engineering design. The overall aim of this project is to establish robust procedures for metrological determination of RS in AM components thereby supporting the use of AM for safety-relevant aerospace- and energy-related components.

## Keywords

Residual stress, life assessment, additive manufacturing, component safety, non-destructive testing.

## Background to the Metrological Challenges

The additive manufacturing (AM) market of metal parts is predicted to grow by 25 % with a value of 4.6 B€ by 2030 however metrological challenges in the qualification of safety-relevant components (e.g. in the aerospace and energy sectors) severely hamper the use of additive manufacturing (AM) in industry. Accurate residual stress (RS) determination is essential for assessing the reliability and remnant life of safety-relevant products/components. In addition, without the knowledge of RS, it would be impossible for modern digital Industry to qualify and certify their parts. Current standards exist for RS determination however these only apply to single-phase materials manufactured with traditional methods. For AM materials with complicated microstructures and texture, these existing standards are unsuitable, creating an enormous obstacle to industrial uptake. This need has been recognised by the European Technology Platform for Additive Manufacturing [1] and in a report commissioned by the European Commission [2]. Laboratory techniques such as the contour method, have been only recently upgraded to provide high spatial resolution, needed for the small cross-sections typical of AM components. However, there are many challenges in order to provide a quantitative and traceable RS analysis of the rough surface and of the defects present in AM components.

Reliable determination of the principal stress axes enables full exploitation of the design capabilities and allows validation of FEM models and in-line monitoring techniques, which can predict life of components in a digital factory. The problem of the precise positioning of the measurement location in the part has been addressed using specific software and metrology approaches however, this approach needs to be re-defined for complex AM parts, capturing their intricate shape. Procedures to reliably establish the principal stress directions are needed in order to exploit the free-form design offered by AM. Precise sample alignment on the measurement table is important to precisely determine the RS distribution. Procedures to define and quantify surface roughness and automate component positioning on the instrument tables are needed, so that the steep RS gradients at surfaces of AM safety-critical parts can be quantitatively determined. It has been shown that different AM scanning strategies yield very different RS distributions. Classic strategies for the determination of the reference strain-free lattice parameter do not apply to AM materials. Therefore, the definition of robust strategies to determine such references are necessary to reliably determine stress values and allow comparison among materials and specimens, providing underpinning traceability. Models, based on so-called single crystal elastic constants (SCEC), are needed to appropriately select the diffraction elastic constants (DEC) required to convert between measured strains and engineering stresses. Currently, there is little data of SCEC of AM materials, so that stresses can be evaluated from measured strains with a precision of 20 % at best. Reliable and traceable laboratory techniques for RS determination need to be calibrated. All current techniques suffer with both the extremely irregular surface and complex form of AM parts. Robust and traceable laboratory techniques (e.g. Barkhausen noise and contour method) need to be established for AM materials and parts. RS has been reported to create large distortions during production and subsequent heat treatments which can render less functional and unsafe during service. Laboratory techniques need to be adapted to measure the RS distribution in complex components.

## Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the protocol.

The JRP shall focus on the traceable measurement and characterisation of residual stress (RS) in additively manufactured (AM) materials. The emphasis shall be on metallic materials and components, but the outcomes should be easily extended to ceramics and composites.

The specific objectives are

1. To establish robust procedures for the location of the measurement points in AM components (with precision better than 20-50 µm and reproducibility better than a 1-5 µm), taking into account the irregular shape of (external and internal) surfaces. This should include the development of redefined alignment procedures (for neutron diffraction and other instruments), as well as using CAD and X-ray tomography data to assist sample positioning.
2. To establish procedures for the determination of the strain-free reference in AM materials with precision and reproducibility better than 50-100 x $10^{-6}$, an error in traceable RS determination of less than 5 % and that allow direct comparison to finite element model (FEM) simulations.
3. To theoretically and experimentally determine the diffraction elastic constants (DECs) in AM materials with a precision better than 2 %. This should also include the development of a robust database of experimental and theoretical values.
4. To calibrate laboratory measurement facilities (that are e.g. based on Barkhausen noise and contour methods) and to develop associated good practice guides for the determination of RS with a focus on magnetic materials. In addition, Finite Element Models and in-line monitoring measurements (e.g. using thermography) should be validated to predict RS distribution in complex components.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, DIs, calibration laboratories), standards developing organisations (ISO, CEN) and end users (e.g. energy, nuclear and aerospace industries).

Proposers shall give priority to work that meets documented industrial needs and include measures to support transfer into industry by cooperation and by standardisation. An active involvement of industrial stakeholders is expected in order to align the project with their needs – both through project steering boards and participation in the research activities.

Proposers should establish the current state of the art, and explain how their proposed project goes beyond this.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 1.5 M€, and has defined an upper limit of 1.8 M€ for this project.

EURAMET also expects the EU Contribution to the external funded partners to not exceed 30 % of the total EU Contribution across all selected projects in this TP.

Any industrial partners that will receive significant benefit from the results of the proposed project are expected to be unfunded partners.

## Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the "end user" community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the "end user" community (e.g. letters of support) is also encouraged.

You should detail how your JRP results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,
- Feed into the development of urgent documentary standards through appropriate standards bodies,

- Transfer knowledge to the aerospace and energy sector.

You should detail other impacts of your proposed JRP as specified in the document "Guide 4: Writing Joint Research Projects (JRPs)"

You should also detail how your approach to realising the objectives will further the aim of EMPIR to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically, the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work.

## Time-scale

The project should be of up to 3 years duration.

## Additional information

The references were provided by PRT submitters; proposers should therefore establish the relevance of any references.


[1] Final AM roadmap published by European Technology Platform for Additive Manufacturing, 2016

[2] EC Report on Identifying current and future application areas, existing industrial value chains and missing competences in the EU, in the area of additive manufacturing (3D-printing), July 2016