

Comparative Applicability Evaluation Of Specific Testing Techniques For Post Exposure Material Creep Behaviour Investigation

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“Post Exposure Material Creep Data Generation and Assessment Procedures”*

Abstract

Assessment of remnant creep strength and creep deformation properties is reviewed with respect to post exposure material testing using small-scale specimens. The potential advantages of three techniques currently available (small-scale conventional creep, impression creep, and small punch creep testing) are that they can provide creep data with minimal invasive material sampling from the in-service components under investigation, without requiring repair of the sampled areas. These advantages are balanced by the experimental nature of the techniques and a lack of standardisation of both the test methods themselves and subsequent use of the data obtained. In addition, doubts remain about the correlation of the data with that obtained from conventional creep tests, and no small-scale data is available for some of the steels or alloy grades of interest. A number of technical aspects such as the mechanical effects of reduced specimen size, the potentially unrepresentative nature of the material sampled, and specimen oxidation effects need deeper consideration than in the case of conventional creep testing. ECCC WG1.1 has tried to assess the advantages and disadvantages of the techniques in terms of their possible adoption by industry, but came to the conclusion that, in spite of the significant progress made in recent years, and in spite of several specific examples of their successful application, none of the available techniques is yet able to be satisfactorily applied in routine residual life assessment.

Keywords

Residual life assessment, small scale creep testing, small punch testing, impression creep testing

Introduction

Companies servicing high temperature plants, which undergo progressive ageing, have an on-going requirement to ensure their continuing structural integrity by remnant life assessment. This may involve a component-specific assessment, which in turn requires component-specific materials creep data. Creep behaviour determination by testing small-scale specimens has the potential to allow for the acquisition of specific materials data for this purpose, without the associated penalty of significant material removal and local component repair.

The ultimate goal of small-scale creep testing must be the production of data, which are equivalent to those obtained by full-scale conventional creep testing, since these will generally have provided the basis of the original design. To be of immediate applicability, small-scale testing should, therefore, be able to deliver remnant material properties such as rupture life, creep strength, times to specific strain, or strain rate, whichever are the critical factors for a given component assessment. Short of this ultimate goal, however, a reliable

method of ranking the creep behaviour of differing components could provide benefits to plant operators, enabling attention to be focused on the most creep expired items and, potentially, a prioritisation of replacement based on their relative assessed remnant creep strength.

An additional essential requirement for the residual life assessor, as well as the plant operator, would be the establishment of universally accepted methodology for these small-scale tests codified by a standard, so that acceptance of the approach by e.g. customers, insurers, boiler inspectors, regulatory bodies, etc could be ensured.

The European Collaborative Creep Committee ECCC is sensitive to all industrial requirements in the field of creep testing and assessment and has therefore promoted within its Working Group 1.1 “Post Exposure Material Creep Data Generation and Assessment Procedures” the production of a comparative evaluation report, that was intended to answer the following questions on the basis of a state of the art survey and collaborative input of European Experts in small scale testing techniques:

1. Objective of the specific post exposure material testing method and type and amount of information produced
2. Validation of results and correlation to conventional material properties that can be used for Residual Life Assessment.
3. Level of general agreement about the testing technique
4. Technical, economical, time schedule advantages for using small scale testing.

The present paper will summarise the results of ECCC WG1.1’s overview [1].

The European Collaborative Creep Committee ECCC

The ECCC was founded in 1991 as voluntary association of a large number of industrial and research companies interested in material creep property assessment, coming from the United Kingdom, Germany, Italy, France, Switzerland, Austria, the Netherlands, Belgium, Denmark, Sweden, Finland, Portugal, Czech Republic and Slovakia. The common purposes are laid down in a Memorandum of Understanding that identifies ECCC’s targets to (1) collate, exchange and jointly assess creep data, (2) support European Standardisation, (3) co-ordinate European creep data generation, (4) develop common research and testing programs, (5) mutually exchange information on high temperature material development, (6) define common procedures for data generation and assessment.

The companies participating in ECCC represent their Nations and cover the whole scope of industries and research organisations dealing with high temperature problems: steel makers, steel product manufacturers, boiler, turbine, plant and equipment builders, utilities and end users, inspection bodies, research institutes, technical universities, and testing houses. ECCC’s work depends mainly on the resources of its members but is additionally supported by limited funding through EC projects like the current Thematic Network “Advanced Creep” (EC contract GTC2-2000-33051).

ECCC is led by the Management Committee (MC), which is the council of the formal representatives of the ECCC member nations and which is supported by a secretariat (currently European Technology Development (ETD)) to manage all administrative and logistical issues arising from the European Project funding activities. ECCC activities are traditionally divided into a freely accessible area and an area restricted to ECCC members only, i.e. organisations belonging to countries that have supplied the requested minimum annual effort. The free area is represented by Working Groups 1 (Creep Data Generation and Assessment Procedures), 1.1 (Post Exposure Material Creep Data Generation and Assessment Procedures) and 1.2 (Creep Crack Initiation Data Generation and Assessment

Procedures). The restricted area is represented by Working Group 3 (Creep Behaviour of Ferritic Steels (WG3.A), Austenitic Steels (WG3.B) and Superalloys (WG3.C)) and Working Group 4 (Creep Behaviour of Components), which are involved with direct data exchange and joint assessment. WG3 produced and up-dates the creep properties data sheets [2], which were inputs to the new European material standards like EN 10028, 10216, etc, while WG1 and its subgroups contribute to testing standardisation (EN 10291, ISO 204, EN 10319, etc.) through the publication of the Recommendation Volumes [1].

ECCC Working Group 1.1

The European Creep Collaborative Committee WG1.1 started in 1998, with the aim of extending creep assessment methods to materials, which have already been exposed to creep for a known or unknown duration. The relevance of this task to industry operating plants (and materials) within the creep regime is that

1. serviced plants could be serviced beyond their original design life,
2. damage of materials under service conditions could be monitored and assessed,
3. information on in-service behaviour could be compared.

All topics were and are objectives for a large number of theoretical and experimental research activities, as well as being applied practically during Plant Life Assessment and Extension Procedures. WG1.1, building on the experiences and results of available European Projects, and on the experiences of major organisations active in the field, aims to give a contribution in unifying terminology, in comparing and recommending creep related testing practices on post service exposed materials (related to conventional and Post Exposure (PE) specific testing techniques), in collating and exchanging PE-data, defining all significant information enabling the use of the data, in advising on the best use of PE-creep data and on the validation of assessment results for residual life computation and also in part on the whole residual life assessment.

WG1.1's results are included in the ECCC Recommendations in part III to each Volume [1].

Small-Scale Testing Techniques

Within WG1.1's scope, and for all companies involved in residual life determination for plant operating at high temperature, the optimised use of methods that can determine remnant creep properties using small specimens, such that non (or less) invasive material sampling can be adopted, has an eminent role.

Three types of small-scale test are currently available:

Small-scale "conventional" creep is essentially a scaled down version of conventional testing utilising specimens of similar geometry loaded in a similar manner to produce creep rates equivalent to those obtained from larger specimens. Several different techniques are known, for instance in [3, 4, 5].

Impression creep utilises indentation at high temperature to produce a constant deformation rate from which a creep strain rate can be derived. Technical details of the technique can be found in [6, 7, 8, 9].

Small punch creep testing uses a punch arrangement to deform flat disc specimens to failure at high temperature, producing a deformation curve similar to that of a conventional creep test. Small punch testing is the best documented technique in the literature eg in [10, 11, 12].

Objectives, Standardisation and Results of Small Scale Creep Testing

Stress State/Deformation Mode and Creep Damage

Conventional small-scale creep testing can be considered to be equivalent to full size creep testing. Small punch testing is essentially a bend test. Impression creep subjects the test specimen to compression. It should be noted that, whereas in conventional uniaxial specimens material will be strained in the direction of the loading axis, this is not the case for disc specimens, so that behaviour orientation effects may not be evaluated properly.

Conventional small-scale and small punch tests have been confirmed by metallurgical investigation to produce the creep damage accumulation processes accompanying extension, eg grain boundary creep cavitation, and ultimately a tensile creep rupture. Impression creep, however, will not generate creep cavities and will not produce a specimen failure, but does, however, produce an “intrinsic” creep deformation rate which can be used to predict tensile creep behaviour.

Modelling of Test Process and Procedure for Correlation to Conventional Properties

Conventional small-scale creep testing can be modelled in the same way as full sized creep specimens [3-5]. Some modelling of strain development and deformation for the small punch test has been carried out at a number of centres or within European projects with interest in this test method (Copernicus and EPERC TTF5), although more work is required in this area. Correlation of small punch with conventional testing is therefore currently made on an empirical basis. The impression creep test, in comparison, is fully supported by a well documented body of finite element studies and the mathematical modelling is regarded as robust [8,9].

Techniques' Standardisation

For all three methods, different laboratories/test houses have adopted or developed different versions of these techniques, the different detailed geometries employed making comparisons of results difficult. A primary goal of modelling work must therefore be to derive an equivalence for the loads applied in the various test geometries and interchangeability of results obtained by different variants of the same technique or different techniques. Even for small punch testing, which is now used at a number of centres in Europe and for which larger effort in standardisation has been made in Copernicus and EPERC, information on load equivalence may not be freely available or generally agreed. In addition, there is evidence that the load equivalence may vary from one class of material to another so that significant experience and background information is needed for test result interpretation. It is believed that additional effort is needed to develop commonly acceptable testing codes for all the three testing techniques.

Specimen Size Effects

In some cases small-scale testing may be immediately representative of the component being investigated, particularly where the component operates in thin sections, eg hot gas path items in combined cycle gas stations and the associated parts of aerospace engines. Where small-scale testing is attempting to simulate thicker section behaviour, however, specimen size must be considered in the light of structurally significant microstructural dimensions. A large grain size may reduce the representativeness of the thickness of a small punch specimen, or the cross section size of the gauge section of a small-scale conventional specimen. In both cases, however, the grain size is unlikely to exceed the

corresponding longer dimension (diameter of the punch disc, axial length of the gauge length of the small-scale conventional specimen) for most materials. There will, therefore, be grain boundaries available to sustain deformation during the test. In the case of nickel based superalloys, however, where exceptionally large grain size can be encountered, grain size may exceed even the larger specimen dimension. Impression creep specimens, for which, in principle, there is no restriction on thickness, will generally have sufficient grains in this direction. A large indenter will also sample numerous grains across the specimen.

Particular difficulties are presented by welds, where e.g. a weld bead dimension would typically exceed the specimen dimensions for small-scale conventional and small punch testing. For impression creep it may be possible to place an indenter within a zone of interest, e.g. heat affected zone or a defined part of it.

A further size effect, which is particularly important for small-scale conventional testing, and to some extent for small punch, is the accuracy with which specimen alignment can be achieved. Misalignment giving rise to additional bending or torsion loads on specimens will be likely to increase experimental scatter.

Except for those cases where the specimen size and test conditions are representative of service conditions, oxidation/depletion effects during the test may also significantly affect the mechanical properties of small specimens. This may be particularly true of longer term tests where testing in a controlled atmosphere may need to be considered for conventional small scale creep testing. Available evidence from small punch testing, however, is that there is not much difference in results when comparing tests in air to tests under argon. In the case of impression creep testing the material being loaded is protected from oxidation to an extent by the indenter, and oxidation is considered less important.

For impression creep and small punch testing, specimen orientation with respect to loading directions within the sampled component has also to be discussed, as the deformation directions may not be obvious.

Component Surface Effects

Sampling will be limited in general to accessible free surfaces, eg the internal bores of hollow rotors, the external surfaces of steam lines or headers. In view of surface effects such as oxidation or carbon depletion, either during manufacture or in service, sampling may obtain material with properties unrepresentative of bulk material properties. Such effects, and their subsequent impact on measured properties, need to be investigated. Vice versa, if these effects play a major role (eg. carburisation in some petrochemical plants), the near surface sampling may become advantageous for material status assessment.

Reproducibility of Results

Because of sampling and testing costs, small-scale testing exercises on actual plant components have generally involved small numbers of specimens. These activities need to be backed up by more extensive repeat testing of material, the availability of which is not a constraint. Because of the factors already discussed, it is likely that small-scale testing will exhibit more scatter than conventional creep tests. Typical variation in nominally identical tests needs to be investigated.

Practical Implications of Small-Scale Testing

Sampling

Guidelines are required on the most appropriate locations to sample and the most reliable sampling techniques. The choice of location requires essentially the same decision that must be made for all remnant life testing:

- sample material in the location that most effectively represents the creep life usage most relevant to the assessment being carried out, with a possible problem of introducing a local repair in an already weakened area , or
- sample material in the less damaged area in order to get a true representation of the component material's original strength.

The most effective sampling techniques will be more a matter of practical experience.

“Less invasive” sampling generally requires particular techniques and often implies dedicated instrumentation that needs to be applied to the component to be sampled. Therefore, limitations to access for sampling devices need to be considered. For particularly inaccessible locations, these considerations need to be extended to cover the capture and removal of the detached sample, the extraction of the sampler, and, in the worst cases, recovery of the situation if sampling fails. Alternatives to mechanical sample extraction include electro-discharge and water jet cutting.

Availability/Costs of Sampling and Testing Services

Most cases of the application of small-scale testing will involve specific plant components, which require assessment, rather than more generic materials evaluations for which larger amounts of material are likely to be available. In these circumstances, cost and timescale for sampling and testing will often be critical and the availability of a choice of acceptable sampling methods and instrumentation, as well as testing facilities with affordable testing costs, will determine the longer term viability of such techniques. A choice of test houses in Europe, important both for competitive costs and availability of machines at short notice may, therefore, become critical.

Use of the Results

A consensus among end users is called for, in relation to the interpretation and application of the results obtained. Ideally, guidelines should be developed on all aspects of sampling, testing and assessment.

An important aspect of the way results are to be used in practice is their acceptability to third parties, e.g. insurers, boiler inspectors, regulatory bodies, etc. The most appropriate way of ensuring this would be the involvement of such organisations in the development of guidelines.

Examples of Application to Plant

The following examples were collated from within the ECCC WG1.1 participants, from organisations that have gained direct experience with the application of the PE-specific testing techniques implying small-scale specimens.

Small Scale Conventional Testing – P22 Interconnection Pipe

A refinery furnace interconnection pipe, inspected during a normal residual life extension routine was found to be cracked close to a circumferential weld. The pipe, made of ASTM A335 grade P22 (2,25 Cr 1 Mo) steel, had been in service for more than 20 years at 535°C and different pressures, conducting semi liquid petroleum derivatives. Before repair was undertaken, a check on the actual creep strength was required, which included small scale conventional creep testing:

- 9 micro-specimens of gauge diameter 1.2 to 1.35mm x 25mm in length were machined from two 50mm x ca. 50mm x 3mm thick samples cut from the redundant thickness of the pipe in two different positions which had experienced the highest operating temperature,
- 10 conventional specimens, conforming to the UNI 5111 standard, were machined from a 500mm full pipe sample cut from a location in a lower temperature area.

Small scale conventional tests were then conducted in parallel under full vacuum (pressure less than 10^{-4} torr) and in high purity argon. For comparison, 10 creep conventional tests were carried out in air. Tests were conducted at temperatures between 550 and 625°C at stresses less than twice the service stress and lasted between 500 and 11,000h (micro-specimens in argon), 100 and 5,000h (micro-specimens in vacuum), 500 and 20,000h (standard specimens in air).

The results of all specimens, including the ECCC base line for a 10CrMo9.10 material [2], are summarised in a Larson-Miller plot in Figure 1. Vacuum and argon micro-specimen tests were in excellent agreement with the standard specimen creep results in air. For shorter durations (low Larson Miller parameter) the rupture strength of the PE-material, independently of the type of test, is clearly smaller than for virgin material, but for higher Larson-Miller parameters, virgin material and PE-material have comparable strength. Figure 2 shows an example of comparable strain vs. time curves as measured on all three test types.

Residual life at service temperature and stress higher than 100,000 h could be determined from the Larson-Miller curve shown in Figure 1. In addition microstructure assessment on sample and creep specimen material confirmed the adequate creep strength of the post exposure material, which exhibited only limited bainite deterioration. The pipe was therefore repaired and kept in service, without any known further problems, for ca. 65.000h.

By comparing the results shown in Figures 1 and 2, it was considered that micro-specimen creep testing in argon, which is less expensive than in vacuum, could be a useful technique for further serviceability evaluation for components, which cannot be easily replaced.

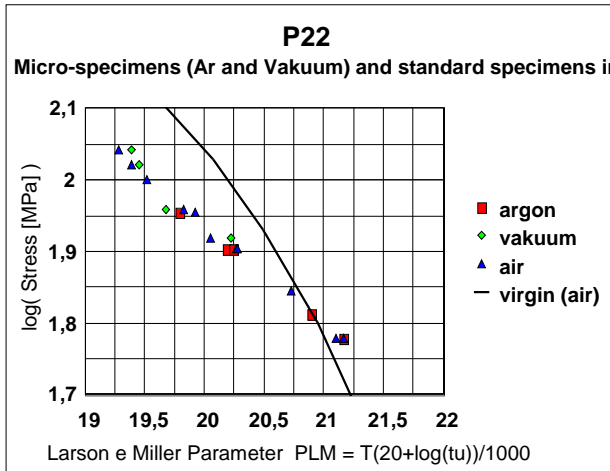


Figure 1: Rupture times of micro-specimen tests in argon and vacuum compared to standard specimen tests in air (same material) and ECCC creep strength for virgin 10CrMo9.10 material.

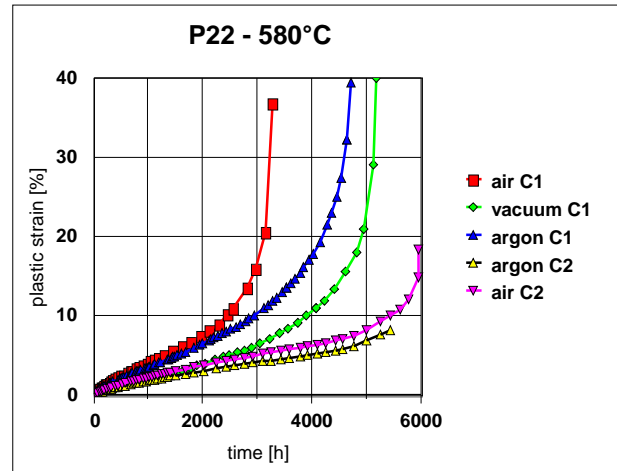


Figure 2: Creep strain vs. time curves for standard specimens in air and micro-specimens in vacuum and argon at 80 MPa (C2) and 83 MPa (C1).

Small Punch and Impression Creep Testing - Modified 9Cr (grade 91) Headers

Following the premature failure of a retrofit modified 9Cr header endplate, a need arose to establish whether similar failures could occur at other power stations. Investigation of the endplate failure, several damaged endplates found by inspection, and a number of premature transition bottle failures, revealed several common features. All the problem forgings, which had been supplied to ASME requirements, showed nitrogen levels in the lower part of the specified range, aluminium levels in the upper part of the specific range, and low hardness. A survey of data supplied by the manufacturers was carried out for other modified 9Cr forgings supplied for retrofit headers. The compositional results, expressed as Log(N/Al), and hardness values are compared with the problem forgings in Figure 3.

Using the results shown in Figure 3, eight further suspect forgings with values of Log(N/Al) and hardness close to those of the problem forgings were located and selected for small scale sampling. This was carried out by a combination of crude sampling (with a hacksaw), where component geometry and access permitted, and miniature scoop sampling. One further forging of interest was available as material surplus to one of the header manufacturing contracts.

A small punch test programme and an impression creep test programme were then carried out on the nine forgings, along with samples of the failed endplate and the header shell adjacent to it. It should be noted that no significant creep damage was found on the shell side of the endplate failure and it was assumed that the shell represented “normal material”. For the small punch tests a single test machine was used, with each test being restricted to 500hrs duration at 191N load and 600°C. For the endplate, this was sufficiently long for the specimen to fail. All other tests were halted short of failure. The minimum deformation rates recorded during the test are shown in Figure 4. It can be seen that the rates and, by implication the creep strengths, of the forgings are similar to each other and to the shell adjacent to the endplate failure. The endplate specimen itself, in contrast, shows a much higher deformation rate, about three times higher than the worst sampled forging.

The impression creep tests were also limited to a single test machine and to test durations less than 500hrs. The minimum creep rates recorded during the test are shown in Figure 5. Again it can be seen that the creep rates and, by implication the creep strengths, of the sampled forgings are similar to each other and significantly lower than that of the endplate.

These results were used to justify a scaling down of the inspection programme initiated for other retrofit modified 9Cr headers immediately after the endplate failure.

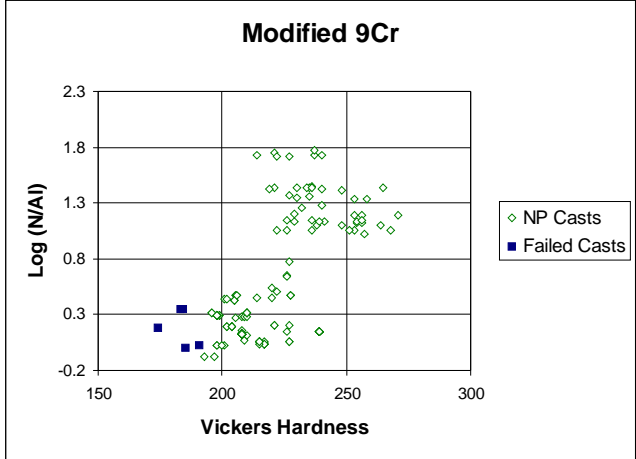


Figure 3. Comparison of investigated Mod9Cr forgings (NP) with recorded failures.

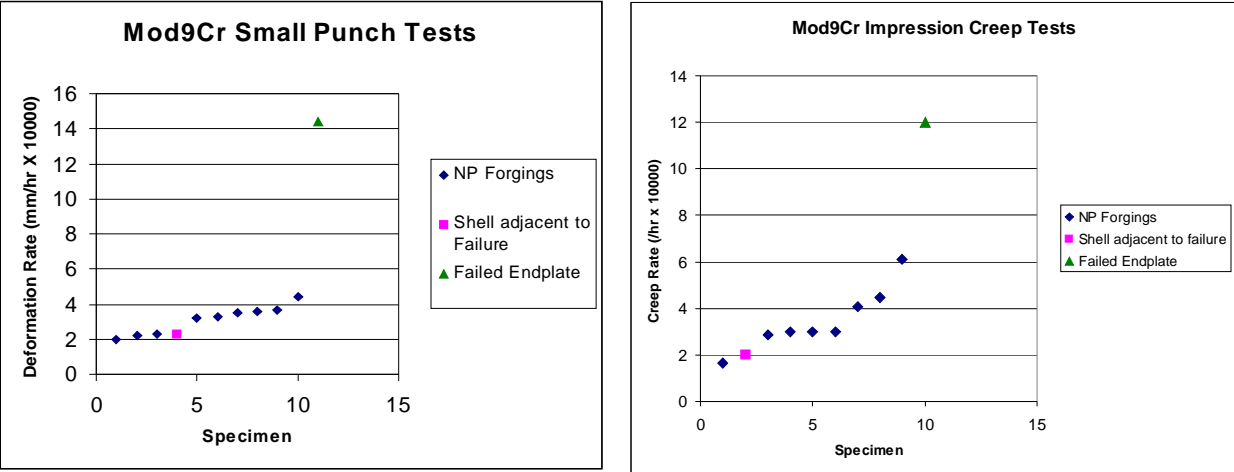


Figure 4. Comparison of small punch deformation rates for investigated forgings (NP), the failed endplate, and unfailed shell (191N/600°C).

Figure 5. Comparison of impression creep rates for investigated forgings (NP), the failed endplate, and unfailed shell (155MPa/600°C).

Conclusions

Each of the three testing methods considered here can be used to provide a qualitative comparison of creep strength. The tests should be equally effective in, for example, ranking a range of casts in order of their creep strength. In particular, the identification of abnormally weak or strong materials should be straightforward.

Where quantitative data, equivalent to those produced by conventional full scale tests are required, the optimum test method depends on which aspects of creep are of greatest relevance. If both creep strain rate and failure behaviour are of interest the small scale conventional test may be the most appropriate. This has the same testing geometry and the material is deformed in the same manner with equivalent creep damage accumulation. Where creep strain rate is the major concern the impression creep test may provide the best option. Although this test method produces deformation without the associated creep damage, the test geometry is well defined by finite element modelling and does appear to provide creep strain rates equivalent to those in full scale conventional tests for a wide range of materials. This test geometry is also particularly useful for measuring creep rates in the different parts of a weldment, ie weld metal, heat affected zone and parent, where these are present to a sufficient extent in the specimen. The potential of small punch testing, which could be similar to that of the impression creep technique, is regarded as being dependent on the harmonisation efforts ongoing in EPERC and potentially in CEN. As conclusive documents from both are not yet available, a final evaluation of the true applicability to the industrial user of this promising technique is still to be explored.

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