THE SMALL PUNCH TEST: AN OVERVIEW OF PREVIOUS RESEARCH

Benedek Kulcsár
MSc student, University of Miskolc, Institute of Energy Engineering and Chemical Machinery
3515 Miskolc, Miskolc-Egyetemváros, e-mail: kulcsar.benedek.zsolt@student.uni-miskolc.hu

Bernadett Spisák
assistant lecturer, University of Miskolc, Institute of Energy Engineering and Chemical Machinery
3515 Miskolc, Miskolc-Egyetemváros, e-mail: bernadett.spisak@uni-miskolc.hu
researcher, Bay Zoltán Nonprofit Ltd. for Applied Research
3519 Miskolc, Iglói u. 2., e-mail: bernadett.spisak@bayzoltan.hu

Abstract
The knowledge of material properties is a key factor in designing structures which withstand the challenges of their lifetime. Small Punch (SP) test is a material testing method which has the advantage of lean material usage. In this study, an overview is presented on the SP testing method. The aim of this paper is to help researchers by collecting articles about different research fields of SP testing. With the experiences from previous research a promising theme is proposed for future analysis in connection with SP testing.

Keywords: *small punch test; overview; FEM*

1. Introduction

Material properties are key factors in designing an engineering structure. The precise knowledge of these information makes the difference between failure and success. For this purpose, dozens of comparable and accurate destructive material testing methods were developed in the past century. The tensile test, creep test, fatigue test, and bend testing are all commonly used and standardised procedures. On the other hand, material properties, acquired from these methods are reliable and precise. Therefore, the replacement of these tests does not seem simple. The drawback of these inspections is the tremendous amount of material used to acquire testing data. This problem induced growing interest in non-destructive inspections. Nowadays there is an expectation of lean material usage in the field of material testing, hence, modern testing methods must be precise in determining multiple properties using low amount of material.

Small punch (SP) testing is a material characterisation method. The most important advantage of the method is the low amount of material used, which makes the procedure considered as non-destructive (Torres et al., 2021). This inspection is favourable in industries where parts need to be tested during operation for degradation monitoring (nuclear industry, petrochemical industry), or very low amount of material is available (for example developmental aero-engine components, turbine case body) (Čížek et al., 2018; Lancaster et al., 2014; Bulloch, 2004). There are various fields of research where this method can be applied. The prediction of material behaviour during plastic deformation, determination of damage model coefficients, artificial intelligence development are just a few examples of the scientific areas which can benefit from the research of SP tests. The purpose of this paper is to bring together the different studies on SP tests by other researchers.

2. Small punch testing

The research of the consequences of radiation became popular with the growing number of nuclear reactors in the middle of the 20th century. The result of this scientific work showed that the monitoring of material properties in nuclear power plants can prevent serious accidents. SP testing was developed for this purpose in the ’80-s to answer the problem of wear due to radiation (Manahan, 1982).

The test setup includes the specimen which has either 3 mm or 8 mm diameter, a lower and an upper die, and a punch. During the test the punch is pushed to the thin circular specimen clamped between the two dies (EN 10371, 2021). The basic measurement setup is shown in *Figure 1*. The punch can be moved in two modes: constant displacement or constant force. The results are usually illustrated as a function of displacement. The displacement can be measured by a crack opening displacement gauge (COD) or by the movement of the head of the testing machine relative to the base of the machine.

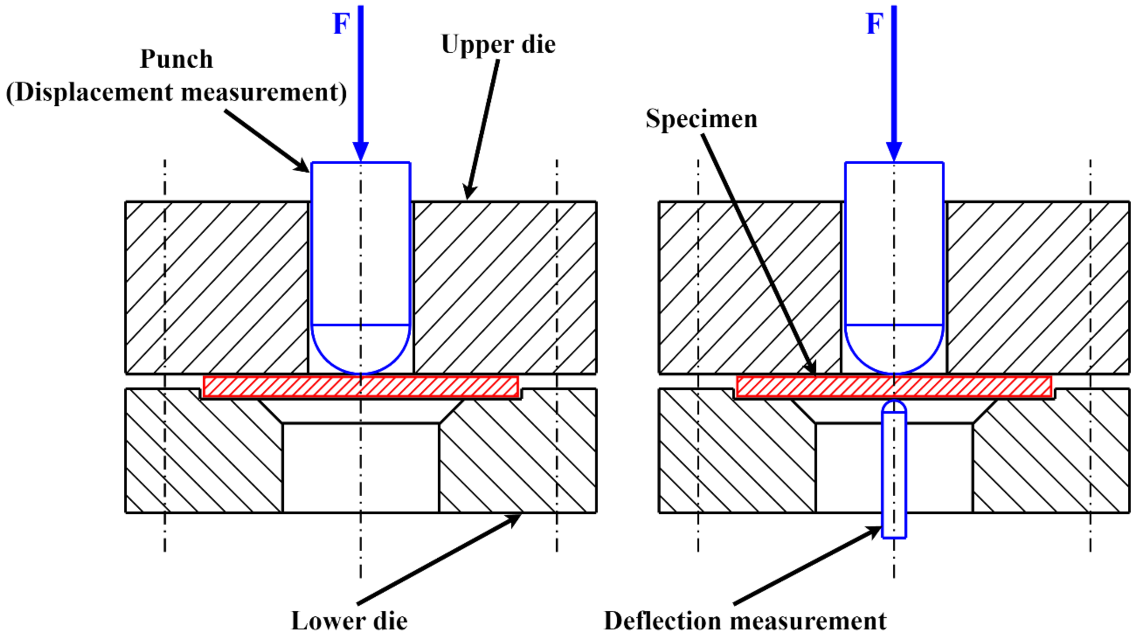

Figure 1. *Configuration of SP test*

Depending on the punch movement, the results of the tests are different. The constant force method provides displacement-time curve for creep behaviour, and the application of constant displacement provides force-displacement curve for elastic and plastic properties (Lotfolahpour et al., 2018). The force-displacement curve can be divided into five sections: (I) elastic bending, (II) plastic bending, (III) membrane stretching and (IV) plastic instability (Simonovski et al., 2017). The failure of the specimen occurs in the fifth section (V). These parts are well displayed in *Figure 2*. which shows a typical force-displacement curve.

The boundaries are often marked by inflection points on the curve. With the help of these sections, multiple material properties can be acquired. In the first section, the angle of the curve can be used to determine the Young modulus, similar to the tensile test force-displacement curve. From the curve, the force connected to yield stress (F_i) and tensile strength (F_m), or strain energy (U) can also be acquired. There are multiple definitions of yield stress interpretation, but the method of Mao and Takahashi is the most used (Mao et al., 1987). This method places the yield point at the intersection of the tangent lines of the I section and the II section of the force-displacement curve. This approach is also used by the standard EN 10371 (EN 10371, 2021).

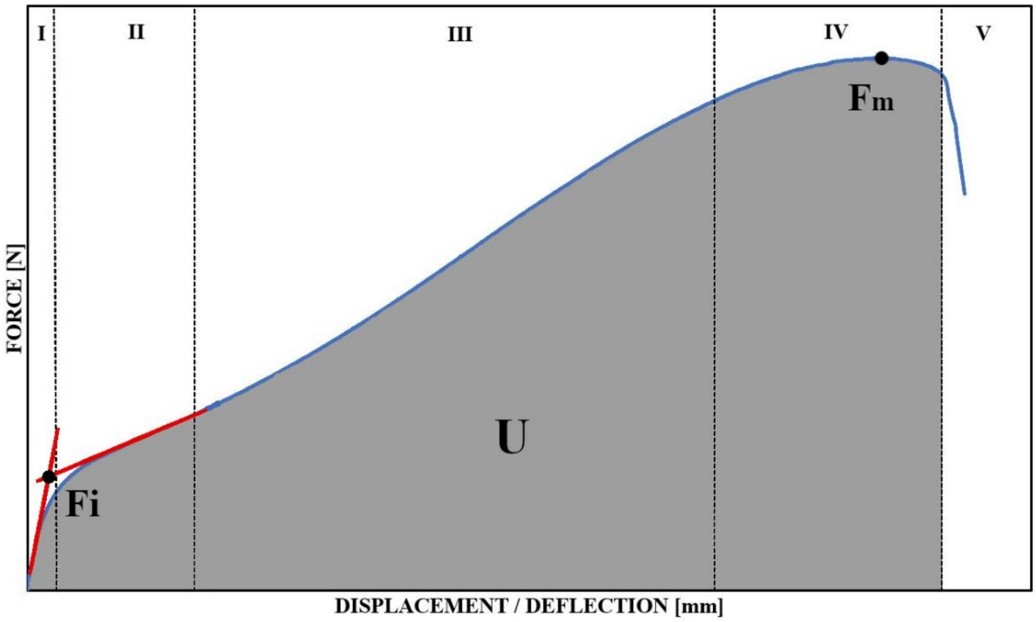

Figure 2. *Force-displacement curve of SP test*

3. EN 10371 – Standard of the SP test

Material testing methods must be comparable and therefore uniformly executed in the different regions of the world. In this aspect, SP testing is not an exception. The EN 10371 is the first European standard on the SP testing method. The first version of the standard was published in 2021. Therefore, some points of the standard are being discussed for further clarification. It goes through the process of the SP test from the sample manufacturing, the testing equipment, the measurement rules, and the environmental requirements to the evaluation of the results. This paper highlights only the main rules of preparation and execution.

The test pieces are usually circular disks, but other shapes can be used which meet the thickness and surface finish requirements (EN 10371, 2021). An important requirement is that the active area of the specimen has to be flat cylindrical shape, and the clamped area must be equal or larger than the same area of the standardized one. There are two standard sizes of specimens, which are listed in *Table 1*.

Table 1. *The accepted sizes of SP specimens*

Diameter [mm]		Thickness [mm]		Ra [µm]
ø8	0	0.5	+0.005	< 0.25
	-0.1		-0.005	
ø3	0	0.25	+0.0025	< 0.25
	-0.025		-0.0025	

The specimens are machined either by a mechanical or electric discharge machining (EDM) extraction method. The specimen should contain at least 5 grains in thickness cross-section, but some exceptions can be accepted for coarse-grain, directionally solidified or single crystal materials. At first the specimen should be machined to the required thickness plus 0,1mm, then with a set of defined roughness abrasive paper the specimens should be ground to the correct thickness. Then the specimen between the two dies is deformed by the punch until fracture. The failure of the specimen is marked by a sudden drop of force if the test was conducted using constant displacement of the crosshead. In the case of small punch creep testing the rapid rise of deflection/displacement marks the failure of the specimen. The important dimensions of the specimen holder are given in the standard as well. For example, the chamfer geometry of the receiving hole is crucial concerning the result of the test noted by M. Abendroth (Abendroth, 2014). Testing in elevated or lowered temperatures is also admitted if the requirements of heating/cooling and measuring are fulfilled. The thermocouple measuring the test temperature is recommended to be in contact with the specimen from the receiving hole side. The standard also defines the rules of SP creep test. The difference between regular SP test and creep SP tests is the movement of the crosshead on the testing machine as explained in the second paragraph.

It has to be noted that the standard is still lacking in some aspects, which includes the effect of the specimen size, missing empirical factors for the standardized specimen (miniaturized version), etc.

4. Previous research

New methods, especially in engineering terms always need proper research to be reliable. It is also important for understanding the processes of testing equipment and behaviour of the specimen. Therefore, an extensive number of studies are published on the topic of SP test. There are a high variety of research fields on this testing method. In this chapter, multiple groups of articles are presented to gather valuable information about SP test. Some of the material properties that are obtainable from SP tests are shown on the left side of *Figure 3*. Material properties connected to this testing method that are not mentioned in this paper are in the "other" group. The right side of the figure presents the computer technologies which can support SP tests.

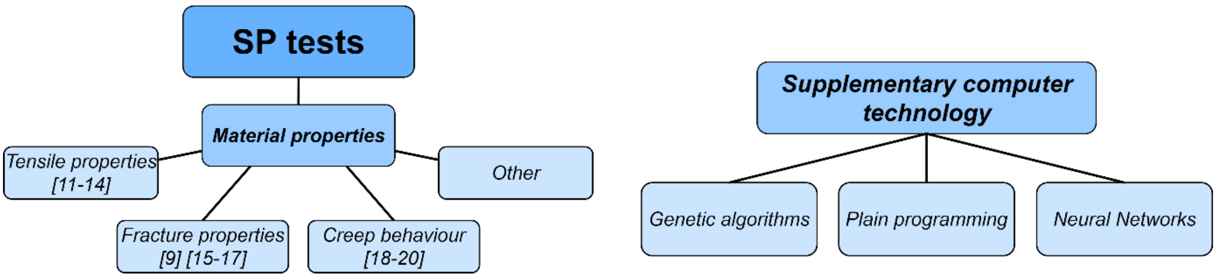

Figure 3. *Research fields and supplementary computer technologies of SP tests*

4.1. Determination of material properties from SP test results

The main goal of the SP test is to give reliable material properties for the new and used structural materials. However, the determination of these parameters must be unambiguous, so the results can be compared. For this reason, multiple studies made attempts to obtain material properties from the SP test result curves.

The identification of the reaction force connected to yield of the material is one of the most researched areas of the topic. Finding correlations with traditional uniaxial material tests can help to promote the uptake and use of SP testing worldwide. Therefore, multiple approaches have been studied. The connection between tensile test and SP test in terms of yield strength and tensile strength has been researched extensively (Leclerc et al., 2021; Song et al., 2012). García et al. claimed, that the ultimate tensile strength is obtained by normalising the maximum load of the SP test result by the thickness of specimen and the displacement at maximum load (García et al., 2014). On the other hand, a study by Altstadt et al. indicated that the correlations of the ultimate tensile test are dependent on material properties (Altstadt et al., 2018).

Obtaining fracture properties are also important for the safe operation of structural materials. A procedure is proposed for the estimation of fracture toughness from miniature SP tests (Mao et al., 1987). Guan et al. and Mao et al. suggested that there is a linear relationship between fracture toughness and biaxial equivalent fracture strain (Guan et al., 2011; Mao et al., 1992). A study by Wang et al. shows that the increment in specimen thickness, the fracture strain and fracture toughness also increase (Wang et al., 2008).

SP tests conducted in elevated temperatures enable the study of creep properties. In comparison with the standard creep test, a similar creep character could be obtained from deflection-time curve of the SP test. A study by Yang et al. stated that the SP creep test can potentially replace the traditional uniaxial creep test (Yang et al., 2017). Wu et al. used an inverse method for extracting creep properties from displacement-time curve (Wu et al., 2019). The study showed that the computing time of the inverse method can be reduced with a pre-defined time step. Dawson et al. claimed that the effect of testing environment (for example testing in argon gas) has an impact on the SP creep behaviour (Dawson et al., 2018). In their research testing in argon increased the time to failure and deflection at failure.

4.2. Computer analysis and SP test

With the widespread use of computers and development in calculation capacities, researchers now have the ability to develop models for the prediction of test results. These models always rely on proper testing data. It was similar in the field of SP tests: a growing number of computer programs and computing methods are used to improve the reliability and consistency of SP tests. Therefore, many publications include programming, finite element method (FEM) models or other numerical calculations.

The largest group of computer-aided research contains FEM modelling. According to a study by M. Abendroth, a two-dimensional axisymmetric model can be a perfect choice for building a simple geometry that preserves important details (Abendroth, 2014). Simonovski et al. claimed, that if the material properties are rate independent, the results are not affected by the loading rate of the punch (Simonovski et al., 2017). Calaf Chica et al. declared that measuring the displacement at the upper point of the specimen is easier, and more precise, than measuring at the bottom (Calaf Chica et al., 2018). The same group of researchers made another study with FEM analysis on the elastic modulus prediction from SP tests (Calaf Chica et al., 2017). The paper acquired correlation factors for a specific geometry and mentioned, that with the standardization process of SP tests, further geometries can be observed.

SP tests and programming are a promising combination of research fields. With the algorithms of the computers, many predictions can be made concerning the material properties extracted from SP test results. The three main computer-aiding methods of SP tests are plain programming, genetic algorithms (GA) and neural networks (NN). The following articles represent studies from these main groups. First, a research by A. Lotfolahpour et al. stated that the dies of the test setup are not completely rigid, which may cause errors in the FEM simulations (Lotfolahpour et al., 2018). The study used connected GA and NN methods. On the other hand, a study written by M. Abendroth et al. claimed that the two dies and the punch can be modelled as rigid bodies (Abendroth et al., 2006). V. D. Vijayanand et al. suggested that both tensile properties and Gurson-Tvergaard-Needleman (GTN) damage model parameters are important for the accurate simulation of the SP test result curve (Vijayanand et al., 2021).

4.3. Determination of GTN parameters

The GTN damage model is a mathematical description of microstructural behaviour of materials during plastic deformation. The model is relying on the nucleation, growth, and coalescence of micro voids of the base material. Therefore, including the GTN model in simulations containing plastic deformation is essential for accurate results. The damage model consists of multiple calculation parameters which varies by material. Computer-aided simulations of SP tests enable the researchers to find the perfect GTN model parameters for each material by an optimisation process. In a study by K. Li et al. the GTN parameters of 316L stainless steel are successfully obtained by an inverse FEM procedure (Li et al., 2018). H. S. Lai et al. acquired the fracture toughness of P91 material using FEM which included GTN parameters (Lai et al., 2023). D. Chen et al. developed an efficient computing model for obtaining GTN parameters with the combination of NN and GA processes (Chen et al., 2021). They claimed that the use of unreasonably large ranges of input parameters may lead to the wrong results.

5. Conclusion

Based on the previously introduced articles the SP testing method is an important topic of research in the past decades. Similar to this paper there were overviews of SP test and summary of research results in the past (Torres et al., 2021). Nowadays the SP test areas of application are extending, bringing new horizons to the researchers (Lai et al., 2023; Sithole et al., 2023; Álvarez et al., 2023). This study aimed to present articles from multiple research fields, to be a starting point of a research work on this topic. Based on this literature overview, the size effect of the allowed specimen sizes is not considered. However, since even the standard allows the use of two different sample sizes, and there are other non-standardized specimens, our future goal is to investigate the deviations between the results of different specimen sizes. These results could help to improve the current SP standard in the future.

6. Acknowledgments

This project has received funding from the Euratom research and training programme 2019-2020 under grant agreement No 945272. The content of this article reflects only the author's view. The European Commission is not responsible for any use that may be made of the information it contains.

References

[1] Torres, J., Gordon, A. P. (2021). Mechanics of the small punch test: a review and qualification of additive manufacturing materials. *Journal of Materials Science*, 56, 10707–10744. **https://doi.org/10.1007/s10853-021-05929-8**

[2] Čížek, P., Kander, L., Stejskalová, Š.: *Industrial applications of small punch test*, 2018 6th International Small Sample Test Techniques Conference, Ubiquity Proceedings. **https://doi.org/10.5334/uproc.13**

[3] Lancaster, R. J., Banik, R., Hurst, R. C., Bache, M. R.: *Application of Small Punch Test Methods to Advanced Manufactured Structures*, 2014 3rd International Conference on Small Scale Test Test Techniques.

[4] Bulloch, J. H. (2004). A study concerning material fracture toughness and some small punch test data for low alloy steels. *Engineering Failure Analysis*, 11, 635–653. **https://doi.org/10.1016/j.engfailanal.2003.05.020**

[5] Manahan, M. P. (1982). *The development of a miniaturized disk bend test for the determination of post-irradiation mechanical behaviour*. Massachusetts Institute of Technology.

[6] EN 10371: Metallic materials - Small punch test method. (2021).

[7] Lotfolahpour, A., Soltani, N., Ganjiani, M., Baharlouei, D. (2018). Parameters identification and validation of plastic-damage model of 304 stainless steel by small punch test at ambient temperature. *Engineering Fracture Mechanics*, 200, 64–74. **https://doi.org/10.1016/j.engfracmech.2018.07.007**

[8] Simonovski, I., Holström, S., Bruchhausen, M. (2017). Small punch tensile testing of curved specimens: Finite element analysis and experiment. *International Journal of Mechanical Sciences*, 120, 204–213. **https://doi.org/10.1016/j.ijmecsci.2016.11.029**

[9] Mao, X., Takahashi, H. (1987). Development of a further-miniaturized specimen of 3mm diameter for TEM disk (3mm) small punch tests. *Journal of Nuclear Materials*, 150, 42–52. **https://doi.org/10.1016/0022-3115(87)90092-4**

[10] Abendroth, M.: *FEM Analysis of Small Punch Tests*, 2014 SSTT Conference.

[11] Leclerc, N., Khosravani, A., Hashemi, S., Miracle, D. B., Kalidindi, S. R. (2021). Correlation of measured load-displacement curves in small punch tests with tensile stress-strain curves. *Acta Materialia*, 204. **https://doi.org/10.1016/j.actamat.2020.116501**

[12] Song, M., Guan, K., Qin, W., Szpunar, J. A. (2012). Comparison of mechanical properties in conventional and small punch tests of fractured anisotropic A350 alloy forging flange. *Nuclear Engineering and Design*, 247, 58–65. **https://doi.org/10.1016/j.nucengdes.2012.03.023**

[13] García, T. E., Rodríguez, C., Belzunce, F. J., Suárez, C. (2014). Estimation of the mechanical properties of metallic materials by means of the small punch test. *Journal of Alloys and Compounds*, 582, 708–717. **https://doi.org/10.1016/j.jallcom.2013.08.009**

[14] Altstadt, E., Houska, M., Simonovski, I., Bruchhausen, M., Holmström, S., Lacalle, R. (2018). On the estimation of ultimate tensile stress from small punch testing. *International Journal of Mechanical Sciences*, 136, 85–93. **https://doi.org/10.1016/j.ijmecsci.2017.12.016**

[15] Guan, K., Hua, L., Wang, Q., Zou, X., Song, M. (2011). Assessment of toughness in long term service CrMo low alloy steel by fracture toughness and small punch test. *Nuclear Engineering and Design*, 241, 1407–1413. **https://doi.org/10.1016/j.nucengdes.2011.01.031**

[16] Mao, X., Takahashi, H., Kodaira, T. (1992). Supersmall punch test to estimate fracture toughness Jic and its application to radiation embrittlement of 2.25Cr-1Mo steel. *Materials Science and Engineering*, 150, 231–236. **https://doi.org/10.1016/0921-5093(92)90116-I**

[17] Wang, Z. X., Shi, H. J., Lu, J., Shi, P., Ma, X. F. (2008). Small punch testing for assessing the fracture properties of the reactor vessel steel with different thicknesses. *Nuclear Engineering and Design*, 238, 3186–3193. **https://doi.org/10.1016/j.nucengdes.2008.07.013**

[18] Yang, S., Ling, X., Zheng, Y. (2017). Creep behaviours evaluation of Incoloy800H by small punch creep test. *Materials Science & Engineering A*, 685, 1–6. **https://doi.org/10.1016/j.msea.2016.12.092**

[19] Wu, W., Xiaozhe, J., Hao, L., Wei, S. (2019). Determination of creep damage properties from small punch creep tests considering pre-straining effect using an inverse approach. *Mechanics of Materials*, 139. **https://doi.org/10.1016/j.mechmat.2019.103171**

[20] Dawson, H., Richardson, M., Gorley, M., Surrey, E.: *The effect of testing environment on small punch creep*, 2018 6th International Small Sample Test Techniques Conference, Ubiquity Proceedings. **https://doi.org/10.5334/uproc.15**

[21] Calaf Chica, J., Díez, P. M. B., Calzada, M. P. (2018). Development of an improved prediction method for the yield strength of steel alloys in the Small Punch Test. *Materials and Design*, 148, 153–166. **https://doi.org/10.1016/j.matdes.2018.03.064**

[22] Calaf Chica, J., Díez, P. M. B., Calzada, M. P. (2017). Improved correlation for elastic modulus prediction of metallic materials in the Small Punch Test. *International Journal of Mechanical Sciences*, 134, 112–122. **https://doi.org/10.1016/j.ijmecsci.2017.10.006**

[23] Abendroth, M., Kuna, M. (2006). Identification of ductile damage and fracture parameters from the small punch test using neural networks. *Engineering Fracture Mechanics*, 73, 710–725. **https://doi.org/10.1016/j.engfracmech.2005.10.007**

[24] Vijayanand, V. D., Mokhtarishirazabad, M., Wang, Y., Gorley, M., Knowles, D. M., Mostafavi, M. (2021). Estimating damage parameters of a CuCrZr alloy subjected to two varying heat treatments using small punch test. *Journal of Nuclear Materials*, 557. **https://doi.org/10.1016/j.jnucmat.2021.153263**

[25] Li, K., Peng, J., Zhou, C. (2018). Construction of whole stress-strain curve by small punch test and inverse finite element. *Results in Physics*, 11, 440–448. **https://doi.org/10.1016/j.rinp.2018.09.024**

[26] Lai, H. S., Jiang, X. (2023). Determination of fracture toughness through small punch test of notched-tube specimen. *Engineering Fracture Mechanics*, 279. **https://doi.org/10.1016/j.engfracmech.2023.109059**

[27] Chen, D., Li, Y., Yang, X., Jiang, W., Guan, L. (2021). Efficient parameters identification of a modified GTN model of ductile fracture using machine learning. *Engineering Fracture Mechanics*, 245. **https://doi.org/10.1016/j.engfracmech.2021.107535**

[28] Lai, H. S., Wang, R., Zhong, Y., Du, P., Guo, J., Huang, Q. (2023). A modified small punch testing scheme to investigate the circumferential mechanical behaviour of nuclear fuel cladding tubes. *Journal of Nuclear Materials*, 583. **https://doi.org/10.1016/j.jnucmat.2023.154517**

[29] Sithole, K., Taylor, C. L., Rouse, J. P., Hyde, C. J. (2023). Multi-scale modelling of the mechanical behaviour of a CoNiCrAlY bond coat alloy during small punch testing. *Materials & Design*, 226. **https://doi.org/10.1016/j.matdes.2023.111601**

[30] Álvarez, G., Arniella, V., Belzunce, F. J., Rodríguez, C. (2023). Study of the influence of current density and displacement rate on hydrogen embrittlement using small punch tests. *Theoretical and Applied Fracture Mechanics*, 125. **https://doi.org/10.1016/j.tafmec.2023.103838**