International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 8, Issue 6, pp 105-109, June-2024

https://doi.org/10.47001/IRJIET/2024.806013

An Interpretation between Small Punch Creep and Uniaxial Tensile Creep Test: Computational and Empirical Approach

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***Abstract* - The relationship between Small Punch (SP) creep testing and uniaxial tensile creep testing is crucial for translating findings from the innovative SP methodology to more conventional testing paradigms. This study involves both computational and empirical approaches to correlate the two testing methods effectively. The computational approach primarily utilizes finite element analysis (FEA) to model and simulate the stress states and deformation behaviors in SP creep tests. The empirical approach involves developing empirical relationships based on experimental data from both SP and uniaxial tensile creep tests. By integrating computational and empirical approaches, researchers can achieve a robust and reliable interpretation of SP creep test data in terms of conventional tensile creep test results.**

Keywords: Small punch creep test; Uniaxial tensile creep test; Creep; High temperature; Finite element analysis; empirical approach.

I. INTRODUCTION

Ensuring the structural integrity of components in operation at high temperatures is essential for safe and reliable performance. Traditionally, assessing the mechanical properties of these components requires material removal, and existing standardized methods often demand a substantial amount of material [1-2]. This challenge has spurred the development of an alternative technique. Initially proposed by Manahan [3] and further refined in Japan [4], the SP test has become a promising and widely adopted method among researchers. The SP creep test has proven effective in evaluating creep behavior [5-9] and estimating the remaining life of high-temperature components [10-12]. Notably, the SP test only necessitates a small volume of material, allowing for direct mechanical testing of localized areas, such as coating regions or heat-affected zones in weldments [13-15].However, the stress state in SP testing is more complex compared to other methods like tensile or miniature tensile tests, despite its relatively straightforward experimental procedure. Consequently, the data derived from SP creep tests cannot be directly applied to conventional test data without proper correlation. A major challenge is establishing how SP test data can be used equivalently to conventional data. Researchers are addressing this by exploring relationships between parameters measured in both conventional and SP creep testing through experimental and computational methods. In the experimental domain, empirical functions are developed to link the force applied in SP testing to the actual stress in conventional testing. This is based on an equivalent uniaxial creep stress that leads to the same rupture time under SP load, using Larson-Miller parameters [16-19]. On the computational side, finite element analysis is employed to examine the relationships between SP load versus equivalent stress and minimum displacement rate versus equivalent creep strain rate. As a result, SP creep testing can be viewed as a static stress test targeting the weakest location of the annular region of specimens within the secondary stage of the SP time-displacement curve [20-23].Through these integrated approaches, researchers aim to establish robust correlations that allow SP creep test data to be interpreted and utilized in the same context as data from conventional tensile creep tests, thereby enhancing the reliability and utility of SP testing in high-temperature component assessment.

This research utilizes a combination of computational modeling and empirical methods to draw correlations between the experimental outcomes of SP tests and uniaxial test techniques. By merging these computational and empirical strategies, scientists can develop a thorough and dependable understanding of SP creep test data, effectively translating it to align with the results from standard tensile creep tests.

II. COMPUTATIONAL APPROACH

In general, the computational approach primarily utilizes finite element analysis (FEA) to model and simulate the stress states and deformation behaviors in SP creep tests. By doing FEA for both models, researchers can map the complex stress distributions observed in SP testing to equivalent stress states in UTC testing. The following steps of this approach are often followed as:

- Finite Element Modeling: The primary step of the computational approach is the creation of detailed FEA models of SP test specimens to simulate their response under load. These models help in understanding the distribution of stress and strain throughout the specimen during the experimental process of both experimental models.
- Evaluation the relation between equivalent stress and strain rates: Deriving equations that relate SP load to equivalent uniaxial stress and displacement rate to equivalent creep strain rate. This is achieved by ensuring that the rupture times and deformation characteristics under SP loading match those predicted for uniaxial tensile creep loading.
- Validation with experimental data: Using experimental data to validate computational models, ensuring that the predicted stress-strain relationships hold true across different material types and test conditions.

Case study 1: In conventional creep testing, the creep properties of each material are determined using the creep power law equation, which relates static stress to the minimum creep strain rate. To derive the creep constants in Norton's creep power law through the SP creep test method, similar equations must be developed to convert SP applied load and punch displacement rates into equivalent stresses and equivalent creep strain rates. Previously, Ma et al. [22] explored a method for measuring the power law creeps constant using the SP creep test with a two-dimensional FEA model. However, the accuracy of the FEA solution can be highly sensitive to the types and aspect ratio of the elements used. The two-dimensional model often relies on the plane strain assumption, which can oversimplify the actual conditions. In the present work, a three-dimensional FEA model was developed to incorporate more realistic geometrical refinements, aiming to achieve a more accurate stress state compared to the simplified two-dimensional model. It should be noted that three-dimensional FEA modeling requires substantial computational time and effort, particularly for implementing mesh refinement at critical locations of interest. By utilizing the three-dimensional FEA model, the study aims to improve the precision of stress and strain rate calculations, thereby enhancing the reliability of the SP creep test method for determining creep properties. This advancement addresses the limitations of previous models and provides a more robust framework for evaluating material behavior under creep conditions.

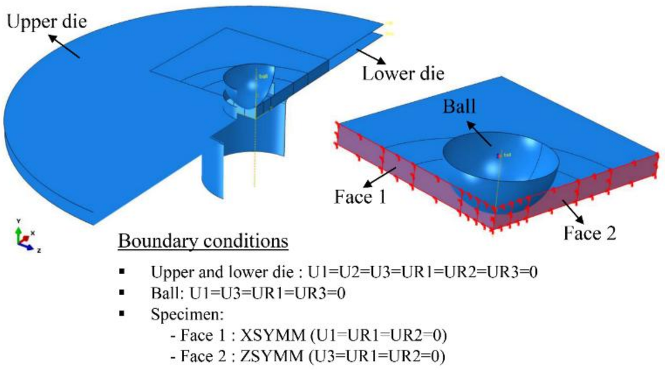

Figure 1: A schematic illustration of three-dimensional finite element small punch creep testing model and boundary conditions

It is also noted that precise characterization of the thickness reduction during the creep-testing process is also essential for understanding material behavior. The geometric model used in this study is schematically shown in Fig. 1. Due to the symmetry of the tested specimen, only a quarter of the specimen was modeled to reduce calculation time. Symmetric boundary constraints were applied on face 1 and plane 2, while both dies were fixed in place. The compressed ball was restricted to vertical movement only. The meshing method was optimized based on Ma's model. Figure 2 illustrates the variation in deformation shape of the small punch creep testing specimen in a three-dimensional finite element analysis, highlighting the equivalent creep strain locations at various creep life fractions under a constant load of 600 N. It is noteworthy that the location of maximum strain did not change significantly with increasing loading time. This stability is crucial for SP creep testing as it implies that the test can be considered a static creep test at the weakest point in the annular region of the specimens. The thickness of the specimen minimized locally at this critical location. Thickness changes were assessed at each time increment corresponding to the increasing depth of punch displacement. Figure 3 presents a comparison between the punch displacement versus creep-testing time curve and the thickness change versus creep-testing time during SP creep-testing, based on finite element analysis results. Additionally, this figure compares the thickness change versus creep-testing time curve from finite element analysis with experimental data observed through interrupted tests [5].The similarity between the thickness change curve and the SP displacement versus time curve during various creep life fractions confirms that the equivalent values of the SP punch displacement rate are practical parameters for analyzing the creep behavior of ductile materials. These values hold the same physical meaning as those obtained from conventional testing methods, reinforcing the utility of the SP creep test in providing reliable and consistent data on material properties under creep conditions.

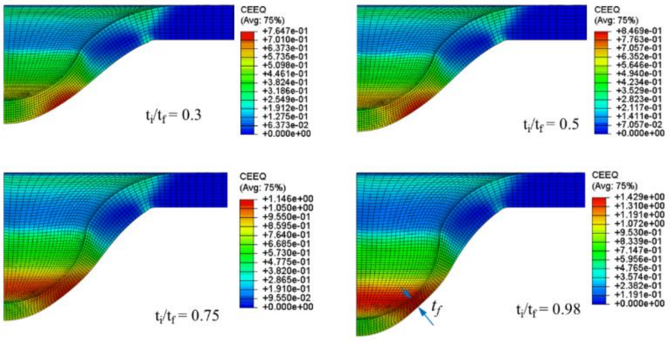

Figure 2: Deformation shape of small punch creep testing specimen in 3-dimensional finite element analysis at various creep life fractions

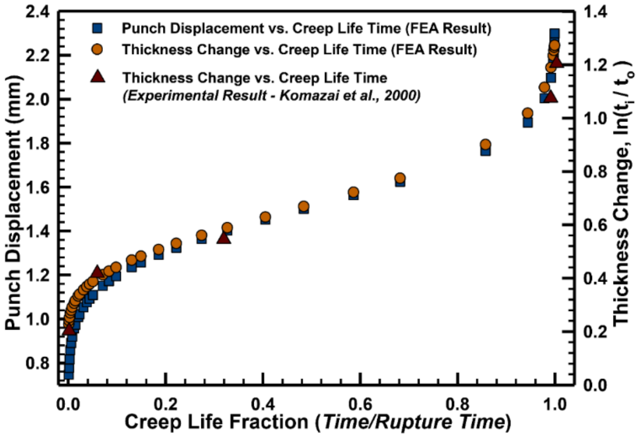

Figure 3: Comparison between punch displacement versus creep life curve and thickness change versus creep life curve during SP creep-testing

In order to derive the converting equations, series analyses at various loading conditions were performed to simulate the SP creep test and the specimen deformation behavior was studied. Reported is the location of local deformation and highest equivalent creep strain that takes place in the same manner as the results in two-dimensional finite element model[22].The applied load versus equivalent stress and displacement rate versus equivalent creep strain rate relationships at middle and bottom points from the weakest location were evaluated for each FEA analysis case. Then, summarized equations that can convert the applied SP stress and the minimum SP displacement rate into equivalent values by using three-dimensional finite element model were found to be as follows.

$$\sigma_e = 0.524P - 11.4 \qquad (1)$$

$$\dot{\varepsilon}_e = 0.798\dot{\delta} + 0.889 \times 10^{-5} \qquad (2)$$

Using Eqs. (1) and (2), the measured SP load and minimum punch displacement rate data from SP creep tests can be readily converted to equivalent values that have similar physical meanings to the parameters measured during uniaxial tensile creep tests. Thus, Eqs. (1) and (2) bridge the gap between SP and uniaxial tensile creep tests, allowing for a unified approach to assessing creep behavior and remaining life in high-temperature components.

III. EMPIRICAL APPROACH

The empirical approach involves developing empirical relationships based on experimental data from both SP and UTC tests. Key steps in this approach include:

- Experimental calibration: Conducting parallel SP and uniaxial tensile tests on the same material to generate a comprehensive dataset. This includes measuring the applied force in SP tests and the corresponding stress in uniaxial tensile tests.
- Empirical function derivation: Establishing empirical functions that correlate the applied force in SP tests with the equivalent uniaxial stress observed in uniaxial tensile tests. These functions are often based on equivalent uniaxial creep stress that yields the same rupture time under SP load, as characterized by Larson-Miller parameters.
- Data fitting and analysis: Using statistical and analytical techniques to fit the experimental data to the derived empirical functions, ensuring a high degree of correlation and predictive accuracy.

Case study 2: To apply SP creep test data with the same relevance as conventional data, particularly in assessing remaining creep life, it is essential to clarify the load conditions in SP creep tests. The most well-known method involves deriving empirical relationships between parameters measured from SP and uniaxial creep tests. Table 1 presents a comparison of the α =F(N)/σ(MPa) ratios reported by various authors for different materials [9, 18-19, 21-22, 25-27]. The value of α ranges from 0.76 to 2.1, indicating a proportional relationship between α and the material's creep ductility. For instance, the α value for modified SUS 304H [18] is approximately equal to that of super duralumin (A2024BE) [26]. Kobayashi reported that a circumferential initial crack formed at approximately 0.5 mm on the bottom surface of the specimen when the lifetime ratio t/tr reached 0.20. This behavior is similar to what was observed for modified SUS 304H in our study, with the slight difference attributed to the variation in SP ball diameter—Kobayashi used a 2.0 mm diameter ball, while our study used a 2.4 mm diameter ball. It is also noted that the α value slightly depends on the testing temperature [19].The α value for T91/P91 steel [21-22] matches the estimated value for T/P24 [27], a well-known ductile material with a similar creep ductile fracture mode. Based on this logic, the expected α value for nickel-based alloys should be less than 1. Although specific α values for nickel-based superalloys are unavailable, Besterci et al. [25] conducted experiments on Al-Al4C3 alloys, which exhibit behavior similar to nickel-based superalloys [28]. The reported α values for these alloys are approximately 0.73-0.79, aligning well with the values discussed here. This suggests that α depends primarily on crack initiation during SP creep tests. Thus, α can be directly evaluated based on crack initiation during SP creep tests, rather than relying on existing empirical functions, as shown in Fig. 4. From this perspective, it is clear that the failure criterion plays a significant role in evaluating this quantity.

Table1: Comparison of empirical relations between the parameters measured from SP and uniaxial creep tests

Reference	Authors	Material	Alpha value, (α)
[25]	Besterci et al., 2010	$Al\text{-}Al_4C_3$ composites	0.73~0.79
[18-19]	Htun et al., 2016, 2017	Modified SUS304H	1.0
[26]	Kobayashi et al., 2010	Super duralumin A2024BE	1.05~1.15
[10]	Parker et al., 1998	CrMoV steel	1.5
[21-22]	Yoon et al., 2009	Group 91 steel	2.0
[27]	Sturm et al., 2004	T/P24 Welding steel	2.10

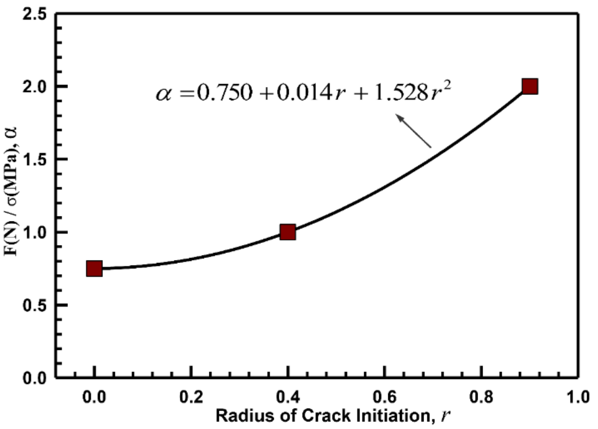

Figure 4: A related function between the radius of crack initiation, (r) and empirical ratios between the parameters measured from SP and uniaxial creep tests

IV. CONCLUSION

The computational and empirical approach to interpreting SP creep testing in terms of uniaxial tensile creep testing were employed provides a comprehensive framework for utilizing the benefits of SP testing while maintaining the reliability and familiarity of conventional testing methods.

This approach can help to extend the applicability of SP test results to a wide range of materials and conditions by validating computational predictions with empirical data. Developing predictive models that can be used to estimate the remaining life and mechanical properties of components based on SP creep test data.

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Citation of this Article:

Hong Bo Dinh. (2024). An Interpretation between Small Punch Creep and Uniaxial Tensile Creep Test: Computational and Empirical Approach. *International Research Journal of Innovations in Engineering and Technology - IRJIET*, 8(6), 105-109. Article DOI https://doi.org/10.47001/IRJIET/2024.806013

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