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Design and evaluation of a ring tension test grip for remote mechanical testing of irradiated tubular specimens

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ABSTRACT

The ring tension test (RTT) is a mechanical testing method for determining bulk mechanical behavior in the circumferential, or hoop direction for tubular materials. The test is especially useful for testing materials with anisotropic mechanical properties, such as zirconium alloys, which are commonly used as nuclear fuel cladding. Anisotropy requires direction-specific testing to determine the hoop strength. Historically, several RTT methods and grips have been used, each method has its strengths and weaknesses, and, in all cases, the measured strength is subject to uncertainty due to variations of the testing geometry and experimental tolerances. Recent analysis has shown that grips with a hemicylindrical mandrel configuration are recommended as the most robust configuration. The two strictest aspects to be controlled are the ability to determine gauge region orientation and closely matching the size of the mandrels to the test specimen. This last requirement is particularly challenging when the dimensions of the specimen vary due to environmental effects such as dimensional changes due to irradiation. This paper presents a new RTT grip designed to incorporate this mandrel shape, hold the gauge at the desired orientation, be suitable for remote operation in a hot-cell environment, and be adaptable for different sizes or variations in the specimen size. The general description, unique design features of the test specimen and grips, are given in detail. The performance of the grips in mechanical testing, including in a remote hot-cell environment, is also provided.

Keywords

Mechanical Testing, Ring Tension Test, Cladding, Remote Design, Mechanical Design

Introduction

For over 50 years the ring tension test (RTT) has been employed to determine hoop direction properties of tubes. Some of the earliest uses date back to 1972, when Prince used hemicylindrical or D-shaped mandrels [1]. It is especially useful for anisotropic tubular materials where the hoop strength cannot be determined from axial tests such as 3D printed materials, welded tubing or pipe, composites and zirconium alloys [2–5]. Despite this particular strength of the test, the RTT can still be used on isotropic materials yielding similar results to that of traditional tensile tests. Furthermore, the RTT is not size dependent, allowing this method to be scaled to different tube sizes, from large diameter pressurized process piping, pressure vessels to small laboratory piping.

FIGURE 1. Comparison of various RTT arrangements. Configurations include a) small mandrels without a gauge, b) large mandrels, often with gauges at the gap, c) “dogbone” insert to prevent inward bending, d) gauges at the top and bottom, and e) a single gauge between the top and the gap.

Since Price, multiple variants on mandrel shape, the inclusion of a specimen gauge, and gauge orientation have been produced. Some examples can be seen in Figure 1 [5–11]. Of these, the mandrels with the “dogbone” shaped central insert, corresponding to configuration (c) in Figure 1 [12], have been widely used in the nuclear industry for testing nuclear fuel cladding [12–15]. Based on this experience, Idaho National Laboratory (INL) implemented the central insert method [12]. However, further testing, as well as finite element analysis (FEA)[16], demonstrated challenges with the implementation of the central insert method for irradiated materials suggesting that a hemicylindrical mandrel grip system would be more ideal.

The testing of irradiated materials requires the test to be performed in a shielded laboratory commonly called a hot-cell to protect personnel from the radiological hazards of the specimens. Experiments are performed within the hot-cells with remote manipulation using master-slave manipulators (MSM) centered around leaded glass shield windows. The nature of the testing environment made it difficult to handle the central insert due to its small size (~8 mm x 6 mm), which also posed a manufacturing challenge. The previously used central insert design caused unwanted stress concentrations at the mandrel-insert interfaces leading to premature yielding, non-uniform deformation, and undesired sensitivity to uncontrollable parameters such as the variable clearance between the mandrels and the specimen diameter. Furthermore, the central insert grips were made to fit a single cladding size requiring new grips for each cladding size available on the market [17,18]. Another challenge in testing irradiated cladding is an inconsistent inside diameter due to inner oxide layer development, warping, bambooing, swelling or fuel remnants bonded to the inside surface of the cladding [19,20]. This can lead to some rings with post-irradiation dimensions that no longer match the nominal fabricated mandrel size. If the ring is too small relative to the grip mandrels, it cannot be tested. Conversely, if the ring is too large, the fit is too loose, the specimen experiences additional bending stresses. While the ring fit is critical, manufacturing new central insert grips for each tube size would be costly and time prohibitive. A new grip design accommodating a variety of tubing diameters would greatly expand testing capability and improve testing flexibility while achieving cost savings.

Analysis also showed that mandrel-specimen friction is a concern [16]. Friction is at the maximum in the option shown in Figure 1 (d) and at the minimum in (a) and (b). However, options (a) and (b) also develop bending and stress concentration at the mandrel gap. Option (e) with the gauge at 45° angle is therefore the compromise between the two, offering lower friction while keeping the gauge away from the mandrel gap.

As anticipated, the unique testing environment of a shielded hot-cell is also a determining factor in the design of the grip. The dexterity of the MSMs is extremely limited so careful design must be implemented to ensure the experiment can be performed within their capabilities. As a result of decades of hosting irradiated experiments, the hot-cell itself is highly radioactively contaminated, making the equipment impossible to remove from the cell after its initial deployment. Replacement, maintenance and troubleshooting therefore must all be performed within the hot-cell remotely using MSMs, further complicating the design and operation of the grip. In some cases, tests on irradiated materials may be carried out in a shielded glovebox rather than a hot-cell, which would relieve some of the remote design considerations. However, often mechanical testing must be performed in a hot-cell due to dose rates, test frame location, or other restrictions. As such, the grip has been designed to operate in either environment with features such as the T handled screws which benefit the operation in either case.

Because of the challenges of remote hot-cell operation a rigorous engineering and multi-phase qualification process must be followed to ensure the equipment can be operated as intended. The development of this new design addresses these challenges to improve both the quality of test data and the practical aspects of performing these tests remotely in a hot-cell environment. The following sections provide a brief description of the resulting grip and specimen design, detailed discussion of the rationale behind key design choices, and important findings from the qualification efforts.

Design Description

For the development of the new grip design, requirements were collected based on previous FEA[16], mechanical testing conditions, hot-cell operation, and manufacturability considerations. The hemicylindrical mandrel shape, a method to control the gauge orientation at a 45° angle, and elimination of the insert were derived from the FEA. The mechanical testing required the grips to be capable of withstanding forces greater than 1 kN (equivalent to an engineering stress of roughly 1000 MPa for a typical 1 mm x 0.5 mm gauge section), implementation of Digital Image Correlation (DIC), and capability of elevated temperature tests of 350°C. Operationally, having a grip that can be easily loaded and unloaded remotely reduces time and risk to the specimens. Without remote handling modifications, the design would be unusable in the hot-cell environment. For the manufacturability, creation of a single grip body that could test a wide variety of cladding and tubing sizes reduces cost and improves turn-around time for test campaigns.

A prototype of this design was then fabricated, enabling a preliminary design review with engineering and remote operations personnel. Operators were able to practice remote handling with this prototype and become familiar with the proposed design and process and provide valuable feedback for the final design. The prototypes design was updated, and the final design was configured. A design review was conducted, the mature grip design was fabricated after incorporation of the collected changes, and both out-of-cell and in-cell qualifications were completed.

SPECIMEN DESCRIPTION

The central insert version of the RTT grips and others utilized a ring sample with two gauges oriented 180° apart [5,12,13,21]. With the development of this new grip, the design was simplified to a single gauged ring. Additionally, maintaining the 45° angle gauge orientation gave the best mix of lower friction, while avoiding the bending stress developed near the mandrel split. However, a method for maintaining the orientation of the gauge was required, and new processes to precisely and reliably machine these critical pieces using a manual mill were also needed. The design solutions to these challenges are described below.

Specimen Gauge and Alignment Notch

The ring specimens were 5 mm wide and utilized a single gauge region. The gauges were typically 3 mm long and 1 mm wide with a 1 mm radius, but other gauge dimensions could be used without any additional modifications to the grips. Initially, it was planned to simply place the ring in the desired orientation, but it was discovered during testing that during loading the ring could shift and the exact gauge angle became ambiguous. A 1 mm radius alignment feature was implemented and oriented at 180° from the top of the mandrel engaging on a mating feature on the grip to ensure the gauge orientation was always known. Figure 2 shows a fabricated ring specimen with alignment notch in place on the grip. The alignment feature placement is such that different mandrels and ring specimen sizes could be used and still engage with the feature; a detailed explanation of the positioning is given in the specimen rationale section.

FIGURE 2. RTT specimen, showing gauge and alignment notch (A) and grip alignment feature and alignment notch on specimen (B).

GRIP DESCRIPTION

The final configuration of the RTT grip is shown in Figure 3. The grip is connected to a traditional tensile load frame via pull rods of sufficient length allowing a clamshell-type furnace to enclose them for elevated temperature testing. The grip is therefore not designed for a specific load frame but was adaptable to different load frames. A more detailed treatment of critical design choices is given in a later section on the grip body rationale.

FIGURE 3. Final assembled RTT grip design (*A*) exploded view of grip quarter (*B*), fully exploded view of assembly (*C*).

The grip body is comprised of four quarters (I-IV), as seen in Figure 3. Quarters I-II and III-IV were joined together via the T-handled screws (C) these two grip halves are then free to slide apart but remained aligned by the guide rods (D). Each quarter had a support block (E) sliding in a slot milled in each grip quarter. Each support block supports the end of a mandrel (B), and a captive support screw (F) is tightened clamping the mandrel into each grip quarter with the support block. A return spring (H) helps to hold the support block in a stable position to help the operators align the grip halves after loading a specimen. Each support block is held into the grip quarters by two small shoulder retaining screws (J) acting as guides, so the support block stays in line during tightening. The alignment feature on the grip body (K) engages with the alignment notch in the ring sample, see Figure 2, to orient the sample during test setup and throughout the duration of the test. On the base of each quarter there is a V-block channel, see Figure 4, holding and aligning the mandrels. V-blocks are commonly used in machining for holding round items of different diameters and provides the grip with the flexibility to handle different mandrel diameters. The current design can handle mandrels with diameters between 6.35- 11.43 mm (0.25-0.45 in). This covers the inside diameter range of most cladding [10,17]. Figure 4 shows two grip quarters each installed with a different sized mandrel demonstrating its ability to hold these separate sizes in the same grip body.

FIGURE 4. RTT grip corners showing V-block feature and ability to hold multiple mandrels of different diameters, 9.45 mm (*A*) 8.28 mm (*B*).

The main grip body was machined from 17-4 precipitate hardened (PH) stainless steel that was heat treated to the H925 condition. 17-4 PH stainless steel has high strength (1200 MPa yield strength) and maintains a greater than 1000 MPa yield strength up to 350°C. The H925 heat treatment was performed by heating to 496°C (925°F) holding that temperature for 4 hours, then allowed to cool in air [22].

Interchangeable Mandrels

The implementation of interchangeable mandrels (part B in Figure 3) addressed some major challenges with small ring testing. It allowed for a single grip to be made for all future planned cladding tests and improved our adaptability for testing. The flexibility to adapt to different specimen sizes means it could be used more universally for other tubing materials. The mandrel halves were made from commercially available gauge pins made of tool steel. Two gauge pins, in the desired size, are purchased and then bisected axially with small steps machined into each end interfacing with the support blocks (E). The steps allow the bisected faces of the mandrels to touch, when assembled in the grip, forming a split cylinder that the ring specimen (A) can slide over. A machined mandrel half can be seen in Figure 5.

FIGURE 5. A 0.326 in (8.28 mm) diameter mandrels half.

Producing mandrels from gauge pins has a variety of practical benefits. The mandrels could be ordered in practically any diameter and are generally stocked in .025 mm (0.001 in) increments, allowing for fine tuning of mandrel to ring size at a low cost.

For high precision, class XX pins could be used, which have diameters held to high tolerances 0.5µm (0.00002 in) and cylindricity, 0.25 µm (0.00001 in). These pins also come with a fine, arithmetic mean roughness (Ra) 0.25 µm (10 µin) surface finish that reduces mandrel-ring fiction. Other classes or specifications of gauge pins can also be used as needed. Ordering the pins saves fabrication time, especially if trying to achieve tight tolerances on mandrel diameters to match the variable cladding inner diameter with the quick turnaround benefits of off-the-shelf components.

The gauge pins are made of strong and hard tool steel, such as American Iron and Steel Institute (AISI) 52100 hardened alloy steel with a hardness of Rc 60-62, Young's Modulus (*E* = 201 GPa) and yield strength of over 1400 MPa [23]. This provides sufficient hardness and mechanical rigidity to the design. Its high strength, even up to 400°C, gives sufficient margin for testing stronger rings of larger diameters or greater wall thickness.

Additional Remote Handling Tooling

Two tools were developed to aid the operators in the loading of samples. The first, a magnetic "quick vise" holding the grip body during loading and a ring push tool to aid in loading of the ring on the mandrels and alignment of the ring, see Figure 6. The vise is an off-the-shelf item modified with two twist lock magnets so that the vise can be magnetically locked down to the hot-cell work table. This allows the MSMs to pull against it as needed during specimen unloading and loading. It is also useful when only one operator is available to load the grips.

FIGURE 6. RTT Grip being held in the quick-vise during in-cell ring specimen loading, one of the two blue hold-down twist lock magnets visible in the background.

The second, a ring push tool is an annular shaped aluminum tool with a hole down the center that slides over the mandrels with a feature that engages with the gauge region of the specimen. This tool is specifically useful when dealing with ring specimens with poor cylindricity and may have a tighter fit on the mandrels. This allows the operators to effectively push the ring down the mandrels while distributing any load across the cross-sectional face of the ring preventing bending prior to mechanical testing. The tool also allows the operators to easily rotate the specimen on the mandrels to orient the alignment features as seen in Figure 7.

FIGURE 7. Ring push/alignment tool use during specimen loading in-cell (*A*) push tool gauge interface (*B*) alignment feature engaged with grip (*C*).

Design Discussion

To arrive at the final design overviewed in the previous sections, several technical and practical considerations were weighed in the decision-making process. Some instances required quantitative analysis to optimize the design, such as determining dimensions of load-bearing components. In other cases, the decision-making process focused on generating innovative solutions to practical constraints, like adopting the use of off-the-shelf gauge pins for mandrels. In every case, each design feature needed to balance aspects of mechanical testing best practice, remote handling, fabrication, and test flexibility. The following sections describe the rationale for the key design features of the mandrels, grip body, specimens, and remote handling features.

MANDREL RATIONALE

The idea to use commercial gauge pins as mandrels initially arose from difficulties with the mandrels of a previous set of central insert grips, resulting in scrapping of the whole grip due to the one-piece construction. In contrast, introducing modularity to the grips by designing replaceable mandrels serves as a risk mitigation strategy. This modular design also allowed us to order off-the-shelf mandrels with precise diameters to match a variety of ring sizes while also avoiding this critical fabrication error in the future. Being able to order precise diameters also allows the mandrels to be easily chosen to match the inside diameter of the specimen minimizing the gaps and their effects on strengths [13,16]. As the idea of removable mandrels was further explored, other benefits and challenges presented themselves.

The material used in the mandrels is of particular importance to the grips' performance. As this material is in direct contact with the specimen, it directly influences the data produced. Many gauge pins are made from a hardened tool steel such as AISI 52100 alloy steel [24], and using off-the-shelf gauge pins limits the material selection. It has a high Rockwell hardness C (Rc) value of 60-62, correlating to poor fatigue properties, difficulty to work and machine, and brittle behavior. However, the mandrels at a minimum need to be harder than the tubular material to be tested such as commercial cladding materials whose hardness values generally do not exceed Rc 37 [25,26]. The high hardness is advantageous in some respects, as it is unlikely to deform, so that the measured displacement will be almost entirely deformation of the ring and not the mandrels. This improves uncertainty of the measurements and provides the most uniform loading of the specimen and reduces compliance in the load train. The gauge pins are inexpensive and can be treated as a consumable item, allowing quick replacement and modification. As a result, using the gauge pins provides more benefits than disadvantages.

The grip holds the mandrels in such a way that they behave similar to a beam with a double-fixed end condition rather than other designs with cantilevered mandrels [9] or with one end fixed and the other simply supported by a faceplate [11,12], see Figure 8. Beam deflection equations (1)-(3)[27] show that, in theory, the center deflection of a cantilevered beam under a central load is 20 times greater than the same beam in a double-fixed end condition, equation (4). For a fixed-end simply supported beam, like the grips with faceplates described above, is 11.4 times less, equation (5). These values were determined by taking the ratio of the maximum center deflection holding the force, length, modulus, and moment of inertia constant.

FIGURE 8. Depiction of different end conditions of RTT grip designs.

$$y_C = \frac{F\left(\frac{l}{2}\right)^2}{6EI}\left(\frac{l}{2} - 3l\right) \tag{1}$$

$$y_{FESS} = \frac{F\left(\frac{l}{2}\right)^2}{96EI}\left(11\left(\frac{l}{2}\right) - 3l\right) \tag{2}$$

$$y_{FF} = \frac{F\,l^3}{192EI} \tag{3}$$

$$\frac{y_c}{y_{FF}} = 20 \tag{4}$$

$$\frac{y_c}{y_{FESS}} = 11.4 \tag{5}$$

where:

y_C = Center deflection of a cantilever beam, mm

y_{FESS} = Center deflection of a fixed end/simply supported beam, mm

y_{FF} = Center deflection of a double fixed-end beam, mm

F = applied force, N

l = beam length, mm

E = Modulus of elasticity, MPa

I = Moment of inertial, mm^4

During loading, the mandrels overcome the preload applied by the support screws, discussed later, and transition to a more mixed-end condition. Since the V-block prevents the ends of the mandrels from deflecting up, which increases stiffness, the true end condition is likely more rigidly fixed than a double simply supported end condition. Although the mandrel ends are not physically pinned, friction between the mandrel steps and support block leads to a quasi-double-fixed end condition. Despite not attaining a true fixed-end condition, a significant decrease in beam deflection is anticipated by designing the mandrel end condition in this way. This may result in an overall equivalent end condition to a one fixed-one single simply supported versions with faceplates. In practice, though, with this style of grip, there is a small amount of deflection that needs to take place before the mandrel can contact the faceplate support due to tolerancing of the mandrel, faceplate, and mounting method of the faceplate. With the grips presented here, mandrel-support block contact is ensured on both ends, reasonably providing reduced mandrel deflection compared to the faceplate version.

Furthermore, this design is superior over pin loaded “D-Blocks” [1,28,29] where the stiffness is limited to the small clevis pin diameter which has to be small enough to fit within the half circle of the “D-Block”. With the testing of larger diameter ring specimens this is less of a concern but in small cladding rings the larger mandrel cross section of this design that resists the shear loading is increased improving the stiffness and reducing compliance.

Frictional forces between the mandrel and the ring have been identified as the main cause of the hemicylindrical mandrel method overpredicting materials strength [16,29]. Thus, reducing mandrel-ring friction is of primary importance, which is accomplished by the smooth mandrel surface finish, the use of a graphite-based lubricant and the 45° angle gauge orientation. The presence of embedded fuel after defueling adds complexity to quantifying this effect [20]. The friction coefficient value can be estimated [13,21,29], and its affect can be accounted for during post processing of the load data [30].

Although off-the-shelf gauge pins are advantageous, the mandrels can be made of any material and are not restricted to gauge pins. Future elevated temperature tests up to and exceeding 650°C, typical of nuclear fuel cladding accident scenarios, could be of particular interest utilizing high nickel or refractory alloys.

Another key aspect of the design is determining and maximizing the load bearing capacity of the grips. The load bearing components can be understood by tracing the load path through the assembly, as shown in Figure 9 (A-B). By inspection, the weakest components (most likely to fail in an overload scenario) are the thin base of the support block (E in Figure 3) and the thin end of the mandrel (B in Figure 3) which is clamped between the V-block and support block.

To investigate the strength and corresponding load bearing capacity of these components, finite element analysis was performed using PTC CREO Parametric 8 Simulate Application. The ring, mandrel, and support blocks were modelled utilizing symmetrical boundary conditions, Figure 9 (D). CREO's AutoGEM meshing tool was used utilizing brick, wedge and tetrahedral elements depending on the geometry. Local mesh refinement was performed on the support block and mandrel, ensuring that sufficiently fine mesh was used for elements in the proximity of peak stresses. Linear analysis was used, and yield strengths were taken at a conservative upper temperature of 400°C; if elements exceeded the yield strength under the different conditions analyzed, the component was considered to have failed. Figure 9 (C) shows the FEA highlighting the high stress areas of the support block and mandrel that were the limiting factors of the grip’s strength.

FIGURE 9. Load path through assembly (*A*) detail view of loads through the support blocks (*B*) FE mesh and deformed model (*C*) FE symmetry constraints and loads (*D*).

To maximize the strength of the support blocks and mandrels an iterative approach was taken adjusting the support block base thickness and mandrel step feature. A third feature to the optimization was the desire to have the support block be compatible with any mandrel size from 6.35-11.43 mm (0.25-0.45 in). To help simplify the optimization, the mandrels with sizes closest to the most common cladding diameter were given priority (~9-9.5 mm diameter). With a mandrel of this size in our FEA we ran multiple analyses adjusting the thicknesses of each part until a balance of stresses within the yield stress values of both materials was achieved. With this optimized support block base thickness and mandrel step size, mandrel diameters were iterated to ensure that mandrels within our target range (6.35-11.43 mm) would function. A table was developed to document the mandrel sizes and the maximum loads that could be applied for that size at room temperature and elevated temperatures, as reported in Table 1.

TABLE 1. Mandrel size ranges and their maximum allowable load at room temperature and elevated temperatures.

Mandrel Diameter Range, mm (in)	Max Allowable Load 20°C, kN (lbf)	Max Allowable Load 350°C, kN (lbf)
6.35-7.59 (0.250-0.299)	1.30 (292.3)	1.10 (247.3)
7.62-8.23 (0.300-0.324)	2.00 (450.0)	1.75 (393.4)
8.26-8.86 (0.325-0.349)	2.25 (505.8)	2.00 (450.0)
8.89-10.13 (0.350-0.399)	2.50 (562.0)	2.25 (505.8)

10.16-11.43 (0.400-0.450)	2.75 (618.2)	2.50 (562.0)

GRIP BODY RATIONALE

To accommodate the advantages of removable mandrels, multiple design features needed to be implemented into the grip body. The ability to hold mandrels of different sizes, sufficient optical and light access for future DIC integration, structural stability, low compliance, and remote handleability were all considered.

The size of the V-block was chosen to fit the range of typical nuclear cladding sizes we planned on testing while trying to maximize this range as much as possible. The grip V-block can physically accommodate larger mandrel diameters than the stated range of 6.35-11.43 mm (0.25-0.45 in), but the limiting factor is the mandrel moves far enough away from the alignment feature that rings cease to engage with the alignment feature with mandrels over 11.43 mm (0.45 in) in diameter. Since this limitation is mainly dependent on the V-block size, this feature could be adjusted to allow for larger or smaller mandrels leaving much of the grip body design the same.

To improve testing, it was desired to have the grip capable of utilizing DIC so that displacement and strain data could be directly collected from the specimen gauge rather than from the crosshead displacement or extensometers. DIC requires direct optical access and is sensitive to lighting conditions so the grip design could not obscure the ring gauge. The curved surface of the ring specimen requires stereo DIC, requiring two cameras with a separation angle between cameras of approximately 20° [31]. With the gauge at a 45° angle rather than normal to the load axis further space was needed to ensure adequate optical access. The gap between the grip quarters was designed to be wide as possible within the other constraints imposed on the grip. There is direct optical access to the gauge region of the ring despite it being oriented at a 45° angle. Approximately 135° of the sample can be viewed from one side allowing enough radial space to implement two cameras for stereo DIC.

The cylindrical bosses on the face of quarters III and IV in Figure 4 structurally connect the two grip halves. The diameter of the cylindrical boss provides a much larger cross-sectional area than the dowel pins that were used in the prototype, improving the stiffness and strength. These features transfer the load between the grip halves and serve as the locating feature aligning the grip corners. This is an improvement over the prototype's dowel pin and shoulder screw to provide the same alignment. In the prototype, aligning the pin, shoulder screw, mating stepped faces and mandrels proved difficult due to the number of features to position simultaneously by the operators. By simplifying this design to a single cylindrical boss, the number of features to align simultaneously is reduced, improving ease of assembly.

Simultaneous alignment of multiple features on the prototype also showed tolerance stack-up issues in the design. Due to the symmetry of the design corners (I-III) and (II-IV) can be interchanged. The grip halves can also be rotated 180° and still be correctly assembled. Small differences in each grip corner could affect the function of the grip. It was desired that there not be a single way required to assemble the grips to reduce the potential error of assembling incorrectly. The cylindrical bosses, previously mentioned, provide much of the alignment of the corners and their tolerances were therefore tightened. The guide rods tolerances were loosened and resulted in the grips being agnostic to a specific assembly configuration and improved consistency in the friction was observed, regardless of the specific assembly configuration.

SPECIMEN RATIONALE

The choice of a single rather than double gauge offered some practical improvements. With the double gauge rings, which gauge would break first was not known, and machining tolerances were less forgiving as both gauges should have very similar cross-sections. It was also difficult to view both gauges at the same time, making the use of DIC challenging. With two gauge regions undergoing deformation at the same time, but only the bulk specimen behavior being recorded, it was difficult to interpret the results, if yielding happened at different grip displacements for each gauge. Additionally, the use of two gauges would preclude the use of the alignment notch. As a result, a new specimen design and a modified machining method was needed.

The previous central insert grip design utilized the central insert to constrain and align the gauge region. This method was no longer achievable with the gauge oriented at a 45° angle requiring a dedicated alignment feature. The size of such a feature needed to be kept as small as possible to limit any effect on the test. Finite element modelling was used to investigate the effect of a variety of potential features on the test. A semicircle alignment feature was the most likely to have minimal impact on test results, with the advantage of being simple to machine with the milling procedures described below. Upon varying alignment feature radii and depths, true semicircle with radius and depth of 1 mm was chosen for its negligible impact. The results in Figure 10 shows that since the thickness of the material around the notch was so much greater than the gauge, the stresses there never exceed the yield strength of the material and no plastic strain occurred, even at ultimate tensile strength (UTS) of the gauge. Therefore, the notch had a negligible impact on the overall elongation of the ring outside of the gauge and could be implemented without altering the test behavior.

FIGURE 10. RTT specimen at moment of UTS, showing plastic strain equivalent (PEEQ) at the alignment notch (*A*) and von Mises stress at the notch (*B*).

Once the sample was aligned and installed into the grips there was not sufficient room within the grip for the ring alignment notch and feature to be disengaged, which maintained the angle within ±1.5° giving assurance to the testing orientation from the beginning to end of the test. Rotation of the specimen could affect the reported strength so holding this parameter as stable as possible was advantageous. The ±1.5° was a function of the tolerances between the alignment feature and the rings alignment notch. The ring was able to freely move side to side, not to the extent that the features could become disengaged but to a point that some small rotation was possible. This rotation was measured using the CAD model of the grip to determine the amount of possible rotation. From previous analysis, if the rotation of the specimen could be kept less than ±5°, the effect on the hemicylindrical mandrel methods was negligible [16].

Irradiated ring specimens are fabricated in the hot-cell utilizing INL's in-cell manual machining capability but unirradiated specimens are typically fabricated out-of-cell using traditional methods for ease of fabrication. Since cladding coatings are currently of particular interest in accident tolerant fuels (ATF) research any coatings or oxide layers are kept intact. This enables the overall measurement of the mechanical behavior of the cladding as it would be in-pile.

The process generally for irradiated cladding specimens is then to cut roughly into 5 mm wide rings using a low-speed diamond saw and send them to the in-cell mill for facing to final width and gauging. The ring samples are then held in a sacrificial aluminum clamping jig to support the ring during machining, preventing gauge deformation during milling. A custom radiused endmill is then used to cut the gauge profile into one side of the ring in a single pass. The aluminum jig is then flipped, and the reverse side of the ring gauge is machined in the same manner. The aluminum clamps are then moved positions and the endmill changed to a 2 mm ball end mill for creating the alignment feature. The gauged and notched ring samples are then sent to an optical microscope for dimensional inspection and then to the load frame for testing.

Since the alignment notch needed to be at a 135° angle with respect to the gauge this could not be achieved with the manual mill limitations, an updated version of the jig provided this function. The jig was made from a hardened steel block and provided two machining positions for the sacrificial clamping jig, A and B, as seen in Figure 11. Position A was normal to the milling direction and B rotated at a 45° angle. Raised bosses and pins aligned the sacrificial aluminum ring clamps. The center of the ring in both positions was held directly in-line, as depicted by the dashed line in Figure 11. This allowed for the mill to be used in both machining locations without needing to re-zero. The sacrificial clamps were also symmetrical so that flipping of the clamp at either position maintained the same center line.

FIGURE 11. Single gauge specimen fabrication process (*A*) jig setup during mock-up testing (*B*) and jig installed in the mill vise in-cell showing a finished milled ring sample in the foreground (*C*).

REMOTE HANDLING RATIONALE

Design and remote operation of equipment requires rigorous process development and forethought. Some tasks which appear simple to accomplish outside of the hot-cell may take hours or may be impossible to complete altogether with the limitation of the MSMs. The equipment cannot simply provide its necessary functions, without planning for remote operation, maintenance and calibration once it was placed in the strong deteriorating gamma fields and argon atmosphere of the hot-cell. The design of the grips must account for robust mechanical testing needs as well as remote system requirements. A strict assembly and disassembly process was developed and implemented into the physical features of the design, ensuring each step in the process was feasible. It also required the creation of additional tooling aids and significant operator practice.

There were a variety of physical features added to aid the operators in its remote use. Captive screws were implemented on all the T-handle and support screws to ensure that they remained with the grip. There were many areas in the hot-cell where items could fall and not be retrieved. Pry slots, Figure 3 (L), ensured the grips could be disassembled if stuck. Knurled MSM grips, Figure 3 (G), aided in disassembly.

Additional tooling was developed as described above to help hold the grip during loading and make that process less time consuming. Finally, operators were able to work with the grip at a specialized testing “mock-up” facility with the same handling capabilities as the hot-cell so that the process steps could be practiced.

Evaluation Results and Discussion

As the final step, to assess the grip and ring specimen designs, tests were conducted with typical experiment parameters. This consisted of characterizing the grips friction and compliance first with an out-of-cell load frame. By measuring the force required to pull the grips apart without any ring loaded on the mandrels, this friction could be characterized and used to correct raw load data.

Design features like the pseudo-double fixed support of the mandrels (see Figure 8.) and the stiff, hardened tool steel for the mandrels reduce compliance. However, compliance of the test train was still important to characterize for correcting raw displacement data. A quasi-rigid thick-walled specimen was loaded with the mandrels in the same manner as a ring specimen to the upper load limit of the grips, 2 kN. The slope of the resulting load-displacement response could be used to correct specimen raw data [12].

FIGURE 12. Compliance curves with different thumb screw preloads.

The compliance testing also provided valuable insights into the consistency and performance of the grips. In out-of-cell testing, some irregularities appeared or disappeared depending on the tightness of the thumbscrews (part F in Figure 3), as seen in Figure 12. When the screws had a high preload, the compliance curve had a steep slope. With less preload, the curve started with a steep slope, then inflected at a load of ~750 N to a shallower slope. However, when screws were given little to no preload, the compliance curve had a single slope across the range of loads investigated. This indicated that tightening the screws added pre-tension to the bolt, keeping the mandrel clamped between the support block and V-block. However, when the load became sufficiently high, it overcame the pre-tension in the thumb screw bolt and changed the end condition, as discussed previously, affecting the stiffness shown by the change in slope seen in Figure 12.

This explanation can be confirmed by comparing the compliance curves for different levels of tightness in the thumbscrews; when the thumbscrews were tighter, the slope change occurred at higher loads, so it was recommended that the thumbscrews have little preload to avoid any compliance change mid-test.

FIGURE 13. Friction (*A*) and compliance (*B*) at room and elevated temperature, dashed lines on the friction curves show the grip weight so the friction force is the difference between the two lines.

After successful characterization testing out-of-cell, the grips were sent into the hot-cell for full testing and qualification, at both room temperature and at 350°C. The friction and compliance characterizations were performed again, see Figure 13, followed by tests of two materials (Zircaloy and a cold-spray chromium-coated cladding

[12]) with unirradiated ring specimens that had been fabricated out-of-cell. While these tests featured unirradiated cladding, sample preparation for irradiated materials may vary. In cases where fuel remnants, an inner-surface oxide layer, or other non-uniform inner surface conditions exist, care should be taken in material preparations to mitigate issues with local contact loading. Four RTTs were prepared, see Figure 14, two at room temperature and two at elevated temperature. This test matrix covered a range of conditions that could be encountered for actual test campaigns. The purpose of these qualification tests was not to determine material properties of novel materials, but to demonstrate reliable and consistent grip behavior in prototypical conditions.

FIGURE 14. MSMs preparing the grip prior to an in-cell ring test, clamshell furnace for elevated temp test visible in the background.

Initially, the elevated temperature friction tests gave inconsistent friction values, and preliminary elevated temperature RTTs with surrogates showed sharp drops in load during the test. It was determined that there was unnecessary friction between the grip body and the guide rods and each time the grip was assembled and disassembled this friction would change slightly based on how tight the T-screws were tightened. At elevated temperature this effect was compounded by the increased friction and differing coefficients of thermal expansion (CTE) between the guide rods and grip bodies materials, 18-8 and 17-4 PH stainless steel, respectively. It was decided to replace the guide rods with ones that were turned down to increase the clearance. From the modularity of the design the guide rods could be easily modified and replaced. Subsequent tests showed lower and more consistent friction values for both the room and elevated temperature tests, resulting in improved stress-strain curves, which are shown in Figure 15. Compliance curves of the in-cell tests remained consistent or better than the central insert grips [12].

FIGURE 15. Stress-strain curves for in-cell Zircaloy and cold spray (CS) coated cladding ring specimens.

Upon successful characterization and adjustment of the grips, the four RTTs were tested. The friction and compliance-corrected engineering stress-strain curves are shown in Figure 15, calculated with a coefficient of friction of 0.1 using the corrections in [16]. A comparison between room and elevated temperature performance confirmed that the test captured the expected temperature response. Both materials showed lower yield and ultimate tensile strengths with greater ductility in the elevated temperature tests, compared to those at room temperature. Comparison of the materials across the temperatures also showed the expected behavior. The uncoated Zircaloy showed lower strengths, and higher uniform elongation values compared to the cold spray coated cladding. Above all, these RTTs show that the grips could produce typical stress-strain curves with expected behavior trends for the test conditions and materials.

Conclusions

A mechanical testing grip was designed to test an optimized version of the ring tension test. The design incorporated features to achieve the hemicylindrical mandrel shape, with a 45° gauge orientation and was specialized for complete remote hot-cell use. This involved a split grip design with MSM handling features, a multi-step assembly process, and other handling aids. The implementation of interchangeable mandrels provides flexibility to adapt to different ring sizes with short turnaround times and decreased testing costs. The design's complexity and multi-piece design resulted in some clearance challenges between moving parts and higher-than-desired friction at elevated temperatures that was dependent on the setup of the grip. Loosening of the fits between these parts resulted in as expected stress-strain curves without compromising grip performance. Successful qualifications test showed the grip provides a robust, improved ring tension test for better determination of circumferential strength of anisotropic nuclear fuel cladding.

Although there are significant improvements as discussed above, it is worth noting some limitations and caveats for using the grip. The use of modular components led to more connections in the load path, which may lead to unwanted compliance. A single piece grip may offer improved compliance, although this modular design has been optimized to reduce load train compliance, leading to limited impact on compliance. Additionally, alignment of the grip components is critical for smooth operation. The grip design limits this effect, but careful attention to fabrication tolerances is vital in optimizing performance.

Future work for this grip includes implementing a high temperature version so that greater than 350°C tests can be performed, using high nickel or refractory alloys or a combination of both. Even with new materials, it is anticipated that the overall design would not need to change, and the geometries shown here could be made simply from these alternate materials.

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REFRENCES

1. E. G. Price, “Hydride orientation and tensile properties of Zr-2.5 wt% Nb pressure tubing hydrided while internally pressurized,” *Can. Metall.* Q. 11(1), 129–138, Taylor & Francis (1972) https://doi.org/10.1179/cmq.1972.11.1.129

2. K. Van Minnebruggen et al., “Effects of specimen geometry and anisotropic material response on the tensile strain capacity of flawed spiral welded pipes,” *Eng. Fract. Mech.* 148, 350–362 (2015) https://doi.org/10.1016/j.engfracmech.2015.04.031

3. M. Travica et al., “Experimental Evaluation of Hoop Stress–Strain State of 3D-Printed Pipe Ring Tensile Specimens” (2022), https://doi.org/10.3390/met12101560

4. F. Bernachy-Barbe, “Anisotropic damage behavior of SiC/SiC composite tubes: Multiaxial testing and damage characterization,” *Compos. Part A* 76, 281–288 (2015), https://doi.org/10.1016/j.compositesa.2015.04.022

5. J. Desquines et al., “The issue of stress state during mechanical tests to assess cladding performance during a reactivity-initiated accident (RIA),” *J. Nucl. Mater.* 412, 250–267 (2011), https://doi.org/10.1016/j.jnucmat.2011.03.015

6. M. Király et al., “Segmented mandrel tests of as-received and hydrogenated WWER fuel cladding tubes,” *Nucl. Eng. Technol.* 53 (2021), https://doi.org/10.1016/j.net.2021.03.019

7. R. Nagy, “Dynamic finite element analysis of segmented mandrel tests of hydrogenated E110 fuel cladding tubes,” *Mater. Today Commun.* 24 (2020), https://doi.org/10.1016/j.mtcomm.2020.101005

8. H. Jiang, “Methodology for mechanical property testing of fuel cladding using an expanding plug wedge test,” *J. Nucl. Mater.* 446, 27–37 (2014), http://doi.org/10.1016/j.jnucmat.2013.11.026

9. M. L. Saux et al., “Behavior and failure of uniformly hydrided Zircaloy-4 fuel claddings between 25°C and 480°C under various stress states, including RIA loading conditions,” *Eng. Fail. Anal.* 17 (2010), https://doi.org/10.1016/j.engfailanal.2009.07.001

10. S. B. Bell et al., “Strength and rupture geometry of un-irradiated C26M FeCrAl under LOCA burst testing conditions,” *J. Nucl. Mater.* 557 (2021), https://doi.org/10.1016/j.jnucmat.2021.153242

11. B. Garrison, M. Gussev, and K. Linton, “Performance of FeCrAl accident tolerant fuel cladding under reactivity insertion accident condition testing,” in *Transactions of the American Nuclear Society* 124, pp. 254–257, American Nuclear Society (2021), https://perma.cc/7PPJ-6S7G

12. D. Kamerman, “Development of axial and ring hoop tension testing methods for nuclear fuel cladding tubes,” *Nucl. Mater. Energy* 31 (2022), https://doi.org/10.1016/j.nme.2022.101175

13. S. Arsene and J. Bai, “A New Approach to Measuring Transverse Properties of Structural Tubing by a Ring Test-Experimental Investigation,” *J. Test. Eval.* 24(6), 26–30 (1996), https://doi.org/10.1520/JTE11461J

14. M. K. Samal, K. S. Balakrishnan, and S. Balakrishnan, “A Practical Approach to Evaluate Stress–Strain Behavior of Remotely Handled Pressure Tubes of Nuclear Reactors Using Ring Tension Test,” *Trans. Indian Inst. Met.* 68(2), 299–310 (2015), https://doi.org/10.1007/s12666-014-0461-0

15. C.S. Seok et al., “The properties of the ring and burst creep of ZIRLO cladding,” *Eng. Fail. Anal.* (2006), https://doi.org/10.1016/j.engfailanal.2005.02.009

16. R. S. Hansen et al., “Evaluation of the Ring Tension Test (RTT) for Robust Determination of Material Strengths,” *Int. J. Solids Struct. (*2023), https://doi.org/10.1016/j.ijsolstr.2023.112471

17. Fast Reactor Working Group, “Nuclear Metal Fuel: Characteristics, Design, Manufacturing, Testing, and Operating History,” Nuclear Regulatory Commission (2018), https://perma.cc/6GRF-MXFS

18. T. Abe and K. Asakura, “2.15 - Uranium Oxide and MOX Production,” in *Comprehensive Nuclear Materials Volume 2: Material Properties/Oxide Fuels for Light Water Reactors and Fast Neutron Reactors* (2012), https://doi.org/10.1016/B978-0-08-056033-5.00036-7

19. S. Aas, “Mechanical Interaction Between Fuel and Cladding,” *Nucl. Eng. Des.* 21, 237–253 (1972), https://doi.org/10.1016/0029-5493(72)90075-1

20. J. T. A. Roberts et al., “On the Pellet-Cladding Interaction Phenomenon,” *Nucl. Technol.* 35(1) (1977), https://doi.org/10.13182/NT77-A31856

21. M. A. Martín-Rengel et al., “Revisiting the method to obtain the mechanical properties of hydrided fuel cladding in the hoop direction,” *J. Nucl. Mater.* 429(1), 276–283 (2012), https://doi.org/10.1016/j.jnucmat.2012.06.003

22. Cleveland-Cliffs Inc., “17-4 PH Stainless Steel Product Bulletin,” Cleveland-Cliffs (2021), https://perma.cc/446A-N9CX

23. Y. B. Guo and C. R. Liu, “Mechanical Properties of Hardened AISI 52100 Steel in Hard Machining Processes,” *J. Manuf. Sci. Eng.* 124(1), 1–9 (2001), https://doi.org/10.1115/1.1413775

24. Meyer Gage Company, Inc, “Individual Gage Pins,” Meyer Gage, 2023, https://perma.cc/33GL-KT65

25. C. Evans, “Micromechanisms and Micromechanics of Zircaloy-4,” (PhD diss., Imperial College London 2014), https://perma.cc/R6P8-3ZJA

26. K. Field et al., “Handbook on the Material Properties of FeCrAl Alloys for Nuclear Power Production Applications,” ORNL/SPR-2018/905, Oak Ridge National Laboratory (2018), https://doi.org/10.2172/1474581

27. J. Shigley and C. Mischke, *Mechanical Engineering Design*, 5th ed., McGraw-Hill, Inc (1989).

28. M. N. Gussev et al., “A correlation-based approach for evaluating mechanical properties of nuclear fuel cladding tubes,” *J. Nucl. Mater.* 574, 154192 (2023), https://doi.org/10.1016/j.jnucmat.2022.154192

29. C. P. Dick and Y. P. Korkolis, “Mechanics and full-field deformation study of the Ring Hoop Tension Test,” *Int. J. Solids Struct.* 51(18), 3042–3057 (2014), https://doi.org/10.1016/j.ijsolstr.2014.04.023

30. R. S. Hansen et al., “Friction Corrections to Improve Accuracy of Cladding Strength Measurements from the Ring Tension Test,” (paper presentation at Water Reactor Fuel Performance Meeting, Xi'an, China, July 17-21 2023), 317–329, https://doi.org/10.1007/978-981-99-7157-2_33

31. P. Reu, “Stereo-rig design: Stereo-angle selection —part 4,” in *Art Appl. DIC* 37(2), 1–2 (2013), https://doi.org/10.1111/ext.12006