Acta Polytechnica **65**(6):696–704, 2025
`https://doi.org/10.14311/AP.2025.65.0696`

Published by the `Czech Technical University in Prague`

TESTING THE DEBRIS FRETTING PHENOMENON OF NEW PERSPECTIVE MATERIALS UNDER LWR CONDITIONS

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Abstract. Despite decades of advancements and research aimed at improving fuel's physical properties, fretting damage to fuel cladding remains a significant challenge. This study outlines the findings of experiments conducted on Zr-1%Nb alloy coated with protective layers composed of chromium-aluminium (CrAl) compounds and other new perspective materials, such as FeCrAl and CrNi alloys, at the Research Centre Řež. The experiments included debris-fretting tests performed under LWR conditions (320 °C and 15 MPa) and microscopic evaluations of groove depths. The primary goals were: (1) to evaluate the debris-fretting resistance of uncoated Zr-1%Nb samples compared to Zr-1%Nb with coatings and new alloys, and (2) to investigate the potential effects of coatings and new materials on the durability of fuel cladding. The conducted experiments and studies confirmed the benefits of the wear resistance of the ATF types of claddings in comparison to the standard Zr-1%Nb cladding material. Various parameters, such as wire wear and the influence of mutual position of the samples, were considered during the testing to provide the most precise insight into the wear resistance of the tested samples.

Keywords: Fuel cladding, coating, Zr-alloys, CrNi alloy, FeCrAl alloy, debris fretting, nuclear fuel damage.

1. Introduction

The fuel cladding plays a crucial role in the performance of a nuclear power unit, serving as the primary safety barrier between the fissile fuel and the coolant, thereby isolating the system from the surrounding environment. In the event of cladding damage, fissile material and radioactive gaseous products can be released into the power plant and potentially into the environment.

While pinpointing the exact causes of leaks is difficult, the most likely cause has been identified with high confidence. As illustrated in Figure 1, debris fretting contributes to a range of defects that affect the fuel rods during operation. However, standard fuel inspections at nuclear power plants are not always able to detect the exact cause of the leaks, making more detailed examinations of defective rods in hot cells necessary [1, 2].

Debris fretting [3] is primarily caused by coolant flow, which generates flow-induced vibrations (FIV). According to a report by Nuclear News and the Electric Power Research Institute (EPRI), most fuel rod failures in the U.S. in 2010 were attributed to wear [4]. This is due to the cladding having comparatively lower wear resistance than more robust materials such as stainless steel, which results in debris, such as peel-offs, wires, and buckles.

Several studies have highlighted the substantial impact of grid-to-rod fretting, particularly in pressurised water reactors [5–7]. Experiences in nuclear power plants [8] confirm these findings, though they do not overshadow the effects of debris fretting damage. Research in this area is limited due to the complex and unpredictable nature of the phenomenon, yet debris fretting remains a critical factor in designing new fuel assemblies, due to possible fuel failure.

A potential solution is the installation of anti-debris filters (ADF) in the bottom nozzles of fuel assemblies. These filters can remove objects with a diameter of >1 mm or those exceeding a thickness of 0.3 mm and a length of 10 mm [9]. Efforts to mitigate debris jamming have also been made through the adoption of the Foreign Material Exclusion (FME) policy, now incorporated into the internal regulations of nuclear power plants.

Another promising approach to minimising the impact of debris involves applying a thin, wear-resistant coating on fuel cladding. Advances in material technologies now enable the application of highly wear-resistant coatings. As thin-film deposition becomes more accessible, it is increasingly regarded as an effective strategy to address grid-to-rod and debris fretting [10]. Numerous R&D initiatives worldwide are dedicated to identifying the most suitable materials for these applications, with active participation from fuel suppliers and research organisations [11, 12].

One of the main challenges in the research and development of coatings is to qualify materials and improve the understanding of how they perform in reactor cores. While the main advantage of coatings is the improved general wear resistance, there is a no-

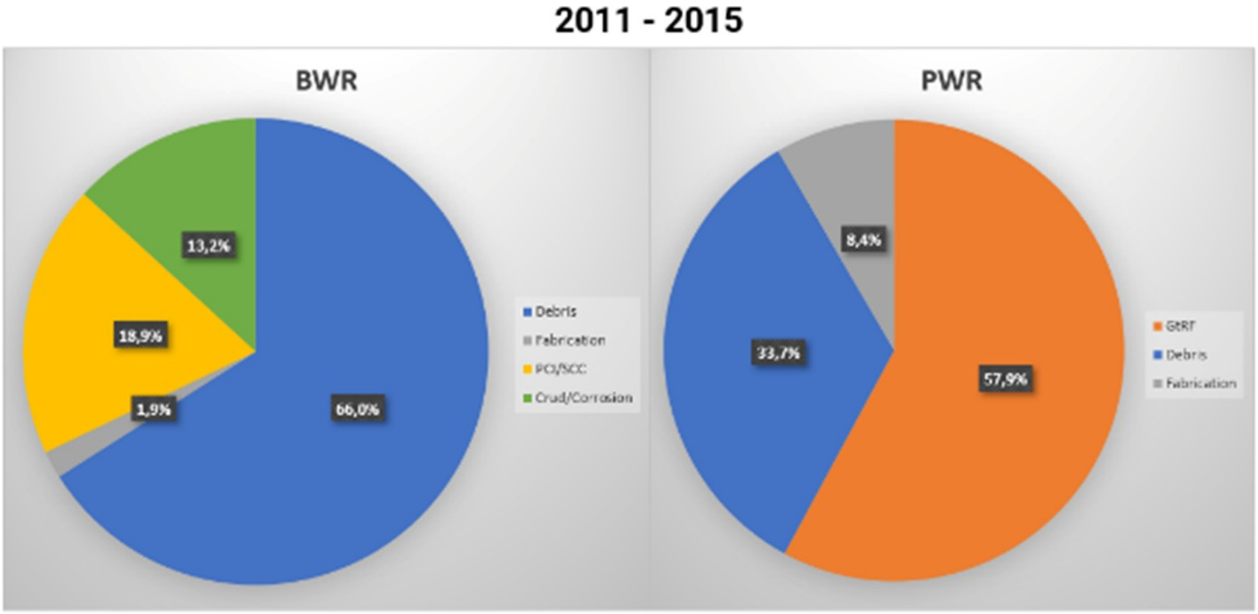

Figure 1. A review of fuel failures in water-cooled reactors (2006–2015) [4].

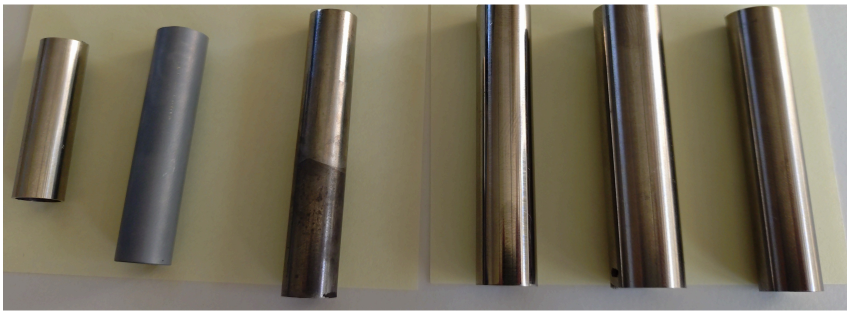

Figure 2. Samples used for tests (from left: CrNi alloy, matrix material with CrAl coating, reference sample Zr-1%Nb, FeCrAl old bar, FeCrAl new bar, FeCrAl new tube).

ticeable lack of current research specifically addressing debris fretting, despite being a leading cause of fuel rod failure.

The Research Centre Řež (CVR), in collaboration with UJP Praha, a.s. (UJP), has developed a specialised methodology for debris fretting testing. Their test facility can conduct multiple tests simultaneously using various coating types. These tests can be performed over short or extended durations and under different conditions (e.g. dry or wet environments, elevated temperatures, gaseous atmospheres). The results from these tests provide a valuable insight into the performance of coating materials intended for real-life applications.

This work shows an insight into the testing conducted on samples (tubes and bars) of nuclear cladding. In this case, the matrix material on which the coating was applied on was a Zr-1%Nb tube. In other cases, the samples were directly made from the nuclear cladding grade alloy.

2. Material and coatings

The Zr-alloy samples used for the tests were provided by UJP Praha a.s. and NFD Japan, as described in [15]. The CrAl coating was applied to the Zr-1%Nb sample using the physical vapour deposition (PVD) method. The thickness of the coating on the cladding material was in the order of micrometres (up to 20 µm). Additionally, new materials that are being considered as progressive fuel cladding materials, such as FeCrAl and CrNi alloys, were also included in the tests. For the FeCrAl alloy, the test used bars that had been previously tested two years ago. For comparison, fresh samples in the form of a tube and a bar were added. The aim of these tests was to evaluate any differences between the old and new types of the samples, as well as the potential influence of the manufacturing process (tube vs. bar). Figure 2 shows all the samples before testing. As the reference sample was previously used in similar tests, the thin oxide layer can be visible. This does not affect the testing procedure.

3. Testing procedure

CVR has developed a testing procedure based on a cyclic contact between cladding specimens and a foreign object imitator – a stainless steel wire mounted on a rotating shaft-like pivot. The rotating pivot is

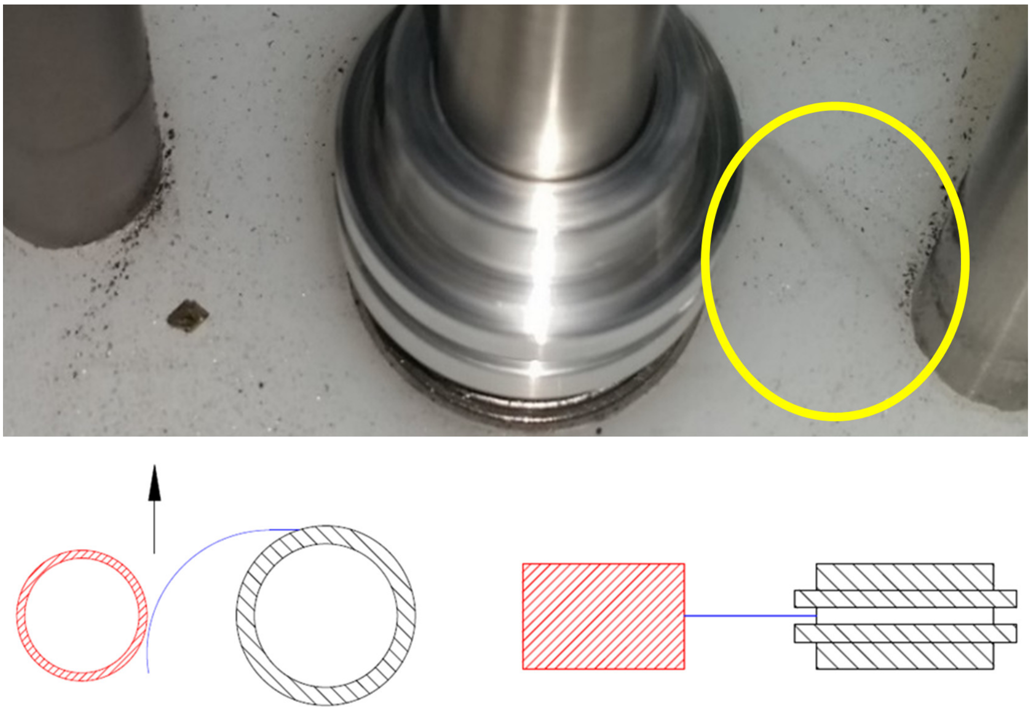

Figure 3. Equipment overview: visible pivot with clamped wire (yellow circle indicates movement) and two specimens [13, 14], schematic representation of the wire (blue), pivot (black), and test specimen (red) positions in the test equipment.

positioned in the centre of the test equipment and is driven by a motor and magnetic clutch at the top. The specimens are placed at the bottom of the autoclave device and fixed in precise positions equidistant from the pivot (Figure 3) in pre-prepared holes in the lower part of the equipment, as described in [14] and [9]. The autoclave (Figure 4) is designed to enable testing at temperatures of up to 350 °C and pressures of up to 15 MPa when assembled and sealed. It can operate in various liquid environments, including boric acid solution. The actual testing conditions described in this paper were 320 °C at 15 MPa. Although the temperature is measured in close proximity to the reference sample, uniform mixing occurs throughout the entire volume of the autoclave due to the rotation of the clamp with the foreign object.

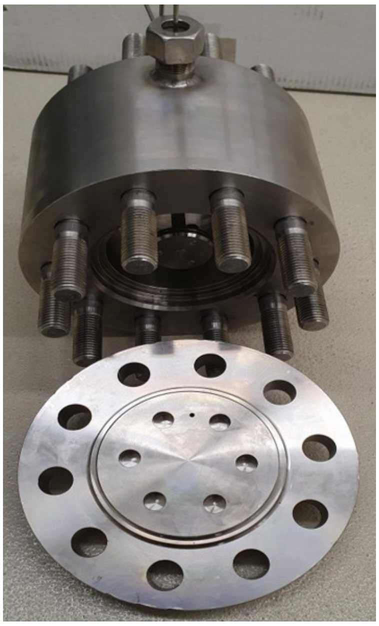

Figure 4. Autoclave used to test the debris fretting phenomenon under LWR conditions.

This device setup ensures a uniform contact between the free end of the wire and each of up to six samples during a single test. The wire serves as a foreign object simulator and is bent to ensure smooth contact with the specimen, with its sliding surface kept almost parallel to the specimen's surface. This configuration simulates a conservative scenario, replicating conditions similar to those in a reactor core, where a wire (a foreign object potentially left behind during maintenance) becomes trapped by the spacer grid. The free end of the wire is subjected to high temperatures, pressure, and intense coolant flow, causing it to bend and reduce friction, which in turn minimises resistance. Due to the shape of the wire, the tests conducted at CVR can take longer to damage the specimen, but they more accurately mimic real-world conditions. Naturally, the flow-induced vibration (FIV) ratio of the wire inside the reactor core can vary based on the coolant flow, which depends on the specific scenario. To simplify this complexity, the pivot in the equipment rotates at a constant speed of 1 000 RPM. The wire is bent over the pivot and secured between two clamps, enhancing test conservatism and optimising test duration. These clamps minimise or eliminate axial vibrations of the wire, en-

		Area [mm^2]	**Max. depth [µm]**
1. set	New wire	0.152814	296.43
	Wire used 1 time	0.151296	289.875
	Wire used 2 times	0.144225	232.134
	Wire used 3 times	0.127762	256.696
2. set	New wire	0.151065	286.151
	Wire used 1 time	0.121788	211.619
	Wire used 2 times	0.104924	207.787

Table 1. Measurement results showing the effect of wire wear.

abling cyclic impacts to be concentrated on a specific area of the specimen [14].

For this experiment, a 0.4 mm diameter wire was selected, a size commonly used in brush heads for nuclear power plant maintenance [9]. Tests conducted under air conditions were used to pre-characterise the specimens prior to autoclave testing in order to establish their baseline behaviour [16].

Four cycle durations were selected to study the impact of coating applications on the fretting resistance of cladding: 100, 200, 300, and 500 minutes. These durations were adapted to match the capacity of the test equipment and were determined through a mechanical evaluation of the system's auxiliary components. The computer in the test system controls the internal pressure using a measuring and regulating valve, while the temperature is monitored with an Inconel thermocouple. This control is based on switching on and off the heating cartridges located in the oven where the autoclave is inserted before the tests begin.

The depth measurements were conducted by means of the Stylus Profilometer Dektak XT (Bruker). The measurement procedure was consistent for all samples, involving axial measurement across the entire groove width along its full length, with a spacing of 0.2 mm between individual measurements. In this way, the measurements of each individual fretting mark created a detailed map covering the entire perimeter of the mark. By connecting the measurement points, it was possible to reflect the volume of material loss and determine the maximum groove depth from this type of 3D map.

4. Factors affecting testing

Before testing the actual samples, the functionality of the testing methodology was verified on an aluminium test body. Comparative tests were conducted to identify the most probable issues and factors affecting the testing process and output consistency. The tests were performed on aluminium tubes with a diameter of 10 mm in a laboratory setting with air as the external environment, for a duration of 100 minutes. Based on the results of these tests, a testing methodology was adjusted to achieve the most consistent and accurate results.

4.1. Effect of wire wear

The effect of the wire wear was investigated by comparing two test sets with different wire states at the start. The first set of experiments was conducted with a new, unworn wire, while subsequent tests used a wire that had undergone some wear, which was expected to negatively impact the groove depth. In the first set, four expositions were conducted, whereas in the second set, only three tests were successfully performed, as the wire broke during the fourth test. The results of the effect of wire wear on the fretting groove geometry are shown in Table 1.

Examining the trend of the removed material area reveals a decreasing pattern, indicating that the more tests that are performed with the same wire, the smaller the affected area (and the depth) becomes, as shown in Figure 5. Additionally, we can see that the results of the first test set are nearly identical, whereas the second test set shows significant variation. Additionally, the discrepancies between the results from the first set of experiments are smaller than those from the second set of tests. This suggests that wire wear has a significant impact on the results, starting from the second test cycle.

4.2. Effect of sample position and material hardness

The effect of the samples' positioning inside the fretting equipment was investigated, as was the sample material hardness. These tests focused on determining the impact of sample positioning within the testing device. Since one of the samples was made of a harder material (stainless steel) compared to aluminium, the study also examined how the different hardness of the tested materials would affect the fretting test. This is important because, during the experiments, the reference material is tested alongside samples with hard coatings, which impact wire wear and consequently alter the resulting groove, especially for the reference sample.

The configuration shown in Figure 6 was chosen to assess the influence of adjacent positions. The assumption is that at 1 000 RPM, the wire does not fully return to its original position before contacting the next sample after making contact with the previous sample. Position 1 served as a control, where

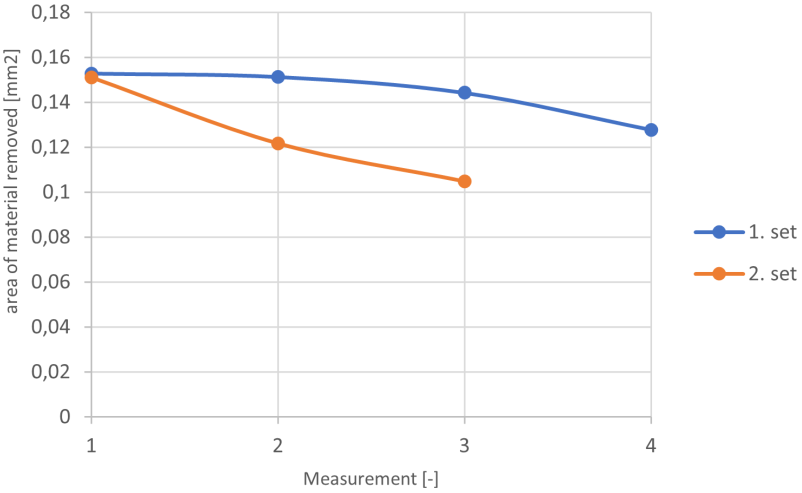

Figure 5. Measurement results of testing the influence of wire damage.

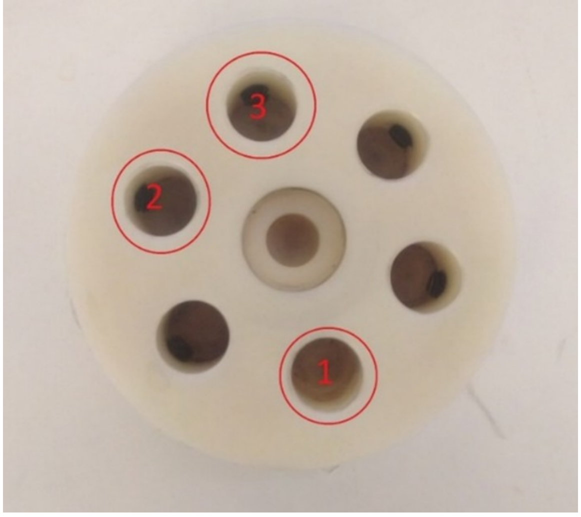

Figure 6. Position 1: Al sample 1, position 2: stainless steel sample, position 3: Al sample 2.

the wire had two empty positions ahead of it when rotating clockwise. The wire was not changed during the testing. Two tests were conducted to investigate this issue – the first one was to determine the effect of sample placement (two samples next to each other vs. a sample with a free position in front of it) and the second one was to place harder material in the testing device along with less resistant samples.

As can be seen in Table 2, the Al sample placed in different positions does not show the same wear after the first test cycle (with a new wire). As shown in Figure 7, the difference in the area of material removed from an individually positioned sample and a sample placed near another is almost double. After the first test, this dependency gradually diminishes.

4.3. Context for real testing

By comparing the results from all the previously described test setups, it can be concluded that the presence of a harder material significantly impacts the test results. When two materials with similar resistance come into contact, increased wire wear also impacts the results for the softer materials in the test setup. In real-sample measurements, such as CrAl, CrNi, or FeCrAl, the testing device is completely filled with these materials (except for the reference material). This suggests that the obtained results are more conservative than the actual conditions. It also offers a more accurate model of the wire's behaviour when clamped inside the fuel, such as when trapped in a spacer grid. By combining different material types in a single test, the impact of wire positioning is reduced or made more uniform. Since all positions are occupied, the wire experiences identical time and distance intervals to relax after the contact with the previous sample. This interval is, however, sufficiently long to ensure a consistent contact with all specimens, ensuring that each sample is affected in the same manner. Because these are tests on fresh samples and because permanent abrasion occurs during the tests (therefore, corrosion does not occur at the point of abrasion), the effects of corrosion are not considered.

All the factors investigated during the Al testing and described here were considered during the exposition of the nominal samples. The results obtained were optimised according to the findings, and in this case, the final results can be considered to be as close as possible to the real in-core conditions.

5. Results

Three different types of tests were conducted at a temperature of 320 °C and an internal pressure of 15 MPa, as demonstrated by the response of the reference specimen to the fretting load. The tests were conducted with FeCrAl bars (one from the 2021 tests and one new), an FeCrAl tube (new), CrNi alloy, and CrAl coating (of 15 µm thickness) on a Zr-1%Nb sample, as shown in Figure 8.

As the Stylus Profilometer was equipped with a nanometric resolution head, the depth measurements of the marks, which are listed in Table 3, were

		Area [mm^2]	Max. depth [µm]
Al sample pos. 1	New wire	0.0889	138.83
	Wire used 1 time	0.058471	101.019
	Wire used 2 times	0.025451	55.3651
	Wire used 3 times	0.026503	54.2533
Al sample pos. 3	New wire	0.047528	110.031
	Wire used 1 time	0.046026	86.0994
	Wire used 2 times	0.033843	61.6031
	Wire used 3 times	0.033407	54.833

Table 2. Measurement results of testing the influence of sample position on wear.

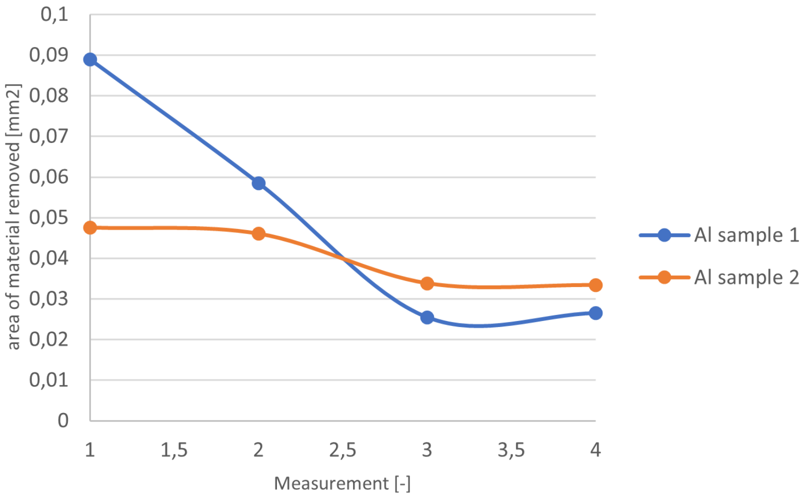

Figure 7. Graphical display of results from testing the influence of the positioning of the aluminium samples.

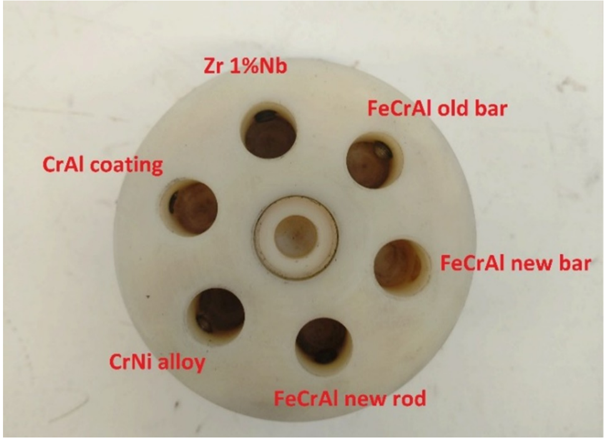

Figure 8. Distribution of test samples in the autoclave.

sufficiently precise. The results remained within the system's accuracy limits, ensuring the validity of all recorded measurements. The values in the table are inverted and determine the value of the fretting mark relative to the surface of the sample.

The results from the first set of experiments, shown in Figure 9, confirm the initial assumption that as the number of cycles increases, the groove created by the wire's abrasion on the sample deepens. This trend is most clearly observed in the reference sample (Zr-1%Nb), which exhibits more significant changes than any other tested material. Among the most suitable materials for the protective coating, CrAl and FeCrAl (older sample) exhibit the lowest groove depth values compared to the reference sample, in which the depth exceeded half of its nominal thickness.

Some anomalies were observed in the samples, particularly during the 200-minute test, when the collet holding the wire likely shifted. This resulted in the formation of a pair of grooves with nearly identical depths, as shown in Figure 10. In this way, the values in parentheses in Table 3 indicate the combined depth of these two grooves.

The results obtained for the FeCrAl samples provided interesting insights. Notably, there is a clear distinction between the older material and the new samples. It is evident that the older bar achieved better wear resistance than the new bar. Several factors could explain this, with the most significant one likely being the differences in material composition. It is possible that the new sample has a different concentration of minor elements (alloying components), which can influence its properties. The direct cause of the identified discrepancy must be further investigated during future planned work.

Another possible explanation are the variations in the manufacturing process of the samples. Differ-

	100 min [μm]	200 min [μm]	300 min [μm]	500 min [μm]
Ref Zr-1%Nb	98.8	69.9 (138)	196	261
CrAl coating	5.1	3.2 (6.4)	7	14
CrNi alloy	4.3	9.7 (19.4)	38	16
FeCrAl tube	6.2	4.6 (9.2)	16	13
FeCrAl new bar	4.6	18 (36)	27	41
FeCrAl old bar	0.8	6 (12)	3	12

Table 3. Results of the depth of the fretting marks on materials tested in an autoclave. Numbers in parentheses refers to doubled fretting marks as, described further in this work.

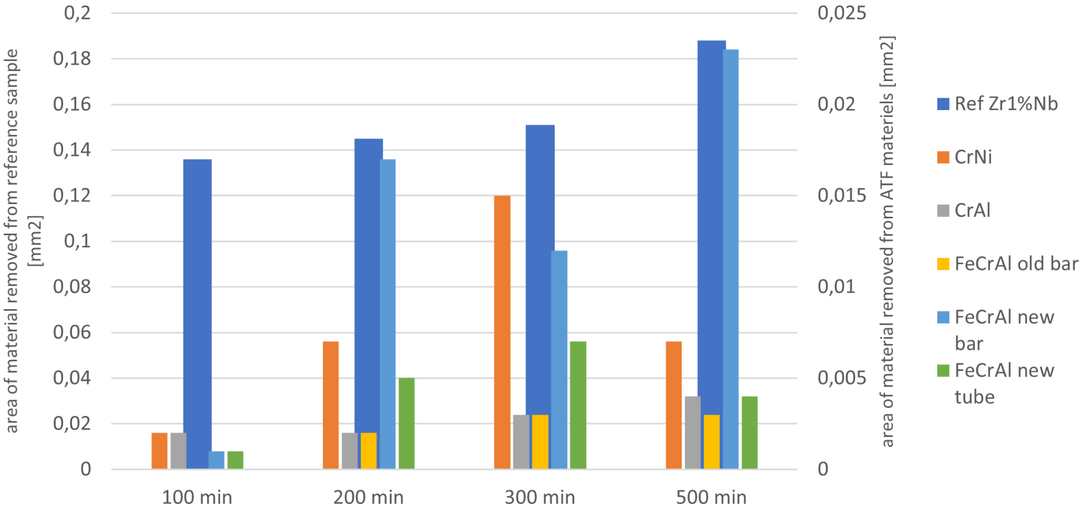

Figure 9. Results from autoclave tests.

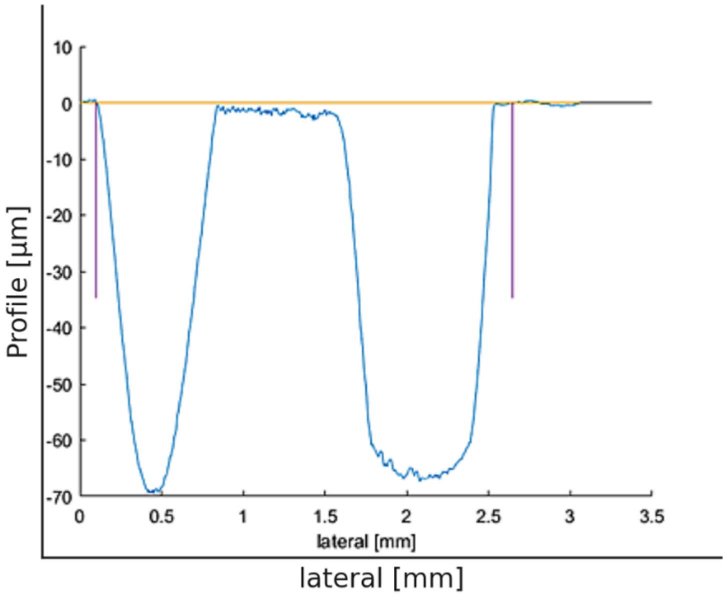

Figure 10. Measurement result at maximum fretting depth on a Zr-1%Nb reference sample.

ent methods of drawing or rolling, whether hot or cold, can result in textural differences within the material, affecting its resistance in specific directions (radial or axial). This is likely the main reason behind another notable finding: the difference between identical materials with different cross-sections. As observed, the tube consistently outperforms the rod in all tests, despite both samples being made from the same supplied material. This difference in results could be due to the different methods of sample production (drawing or rolling). The method affects the structure of the material and thus its resistance to different types of damage in different directions.

6. Conclusion

The conducted experiments have provided valuable insights into the debris fretting phenomenon and its impact on various protective coatings applied to currently used nuclear fuel cladding or new cladding materials. The results confirm that as the number of cycles increases, the groove depth caused by wire abrasion also deepens, with the reference material (Zr-1%Nb) being the most affected. Among the tested specimens, CrAl coating on Zr-based matrix cladding material and FeCrAl alloys have demonstrated the highest resistance to wear, significantly outperforming the reference material, where the groove depth exceeded half of its nominal thickness.

The tests further revealed that wire wear has a considerable influence on measurement consistency. The initial tests, performed with a new wire, yielded more uniform results, whereas subsequent tests using a worn wire produced more variable results. Additionally, the positioning within the testing setup was found to play a crucial role in the results, as samples placed closer together showed nearly double the material removal as compared to isolated samples. Both those factors were taken into consideration during the testing of nominal samples.

Comparative tests between different FeCrAl samples highlighted a noticeable performance gap between older and newly produced materials. The older rod exhibited superior wear resistance. Notably, samples with tubular cross-sections consistently achieved better results than rod-shaped samples, despite being made from the same material.

Finally, anomalies were detected in the testing setup, particularly in the 200-minute test, where a likely shift in the collet holding the wire led to the formation of dual grooves of nearly identical depth. Aggregated measurements and output analysis confirmed the validity of these results, which follow the predicted trend.

Overall, these findings emphasise the crucial role of material selection, surface coatings, and testing conditions in mitigating debris fretting damage. Future work should focus on refining the test methodology, evaluating the durability of coatings in high-temperature and high-pressure environments, and further optimising the experimental setup in order to minimise variability and improve the consistency of results. The obtained results show that ATF cladding is significantly superior to standard cladding materials in terms of its performance inside a power reactor.

List of symbols

ADF	Anti-Debris Filter
ATF	Accident Tolerant Fuel
PVD	Physical Vapor Deposition
NFD	Nippon Nuclear Fuel Development Co., Ltd.
CVR	Research Centre Řež
EPRI	Electric Power Research Institute
FIV	Flow Induced Vibrations
FME	Foreign Material Exclusion
GTRF	Grid to Rod Fretting
R&D	Research and Development
UJP	UJP Praha a.s.

Acknowledgements

The presented work has been realised within the Institutional Support by Ministry of Industry and Trade of the Czech Republic, No. 11/2023.

The presented results were obtained using the CICRR infrastructure, which is financially supported by the Ministry of Education, Youth and Sports – project LM2023041.

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