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TRANSITION FRACTURE TOUGHNESS CHARACTERIZATION OF EUROFER97 STEEL USING PRE-CRACKED MINIATURE MULTI-NOTCH BEND BAR SPECIMENS

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ABSTRACT

In this report, we present the feasibility study of using pre-cracked miniature multi-notch bend bar specimens (M4CVN) with a dimension of 45mm (length) x 3.3mm (width) x 1.65mm (thickness) to characterize the transition fracture toughness of Eurofer97 based on the ASTM E1921 Master Curve method. From literature survey results, we did not find any obvious specimen size effects on the measured fracture toughness of unirradiated Eurofer97. Nonetheless, in order to exclude the specimen size effect on the measured fracture toughness of neutron irradiated Eurofer97, comparison of results obtained from larger size specimens with those from smaller size specimens after neutron irradiation is necessary, which is not practical and can be formidably expensive. However, limited literature results indicate that the transition fracture toughness of Eurofer97 obtained from different specimen sizes and geometries followed the similar irradiation embrittlement trend. We then described the newly designed experimental setup to be used for testing neutron irradiated Eurofer97 pre-cracked M4CVN bend bars in the hot cell. We recently used the same setup for testing neutron irradiated F82H pre-cracked miniature multi-notch bend bars with great success. Considering the similarity in materials, specimen types, and the nature of tests between Eurofer97 and F82H, we believe the newly designed experimental setup can be used successfully in fracture toughness testing of Eurofer97 pre-cracked M4CVN specimens.

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1. INTRODUCTION

Eurofer97 is one of the leading candidates of reduced activation ferritic martensitic (RAFM) steels for first wall structural materials of early demonstration fusion power plants. During fusion plant operation, high neutron irradiation damage on first wall materials can cause irradiation embrittlement and reduce the fracture toughness of RAFM steels. Therefore, it is critical to select proper testing techniques to characterize the fracture toughness of RAFM steels with high fidelity prior to and after neutron irradiation. This is especially true for testing neutron irradiated specimens which are usually much smaller than standard size specimens due to the limited volume of irradiation facilities and low occupational dose advantage of small size specimens after irradiation. In this report, we present the feasibility study of using pre-cracked miniature multi-notch bend bar specimens (M4CVN) with a dimension of 45mm (length) x 3.3mm (width) x 1.65mm (thickness) to characterize the transition fracture toughness of Eurofer97 based on the ASTM E1921 Master Curve method. We will discuss results in literature regarding the specimen size effect on the measured Eurofer97 fracture toughness. Then we will describe the experimental setup to be used in testing neutron irradiated Eurofer97 pre-cracked M4CVN bend bars in the shielded hot cell facility.

2. LITERATURE SURVEY

Specimens of a wide variety of sizes have been used to measure the transition fracture toughness of unirradiated Eurofer97 in literature. Table 2.1 summarizes the results in our literature survey. Based on the ASTM E1921 Master Curve transition temperature, T_0, and specimen thickness in Table 2.1, Figure 2.1 shows no obvious specimen size effect on the measured fracture toughness of unirradiated Eurofer97. Indeed, as mentioned in Ref. [8], the transition temperature for Eurofer97 appears to be independent of specimen type and specimen thickness. In addition, the specimen size effect on the transition fracture toughness of F82H steel, another RAFM steel with similar structure and composition as Eurofer97, has been studied for the unirradiated condition at Oak Ridge National Laboratory (ORNL) and no obvious size effect was observed [9, 10,]. As shown in Figure 2.2, fracture toughness results from pre-cracked miniature 3-point bend specimens (same cross-section as M4CVN) are comparable with those from larger size specimens, e.g. 1T C(T), 0.4T C(T), and 0.18T DC(T) (disk compact tension specimen). Testing of only 10 pre-cracked miniature 3-point bend specimens at a relatively lower temperature near the lower shelf yielded similar Master Curve transition temperature T_0 as testing plenty of larger size specimens.

Table 2.1 Transition fracture toughness results of unirradiated Eurofer97 using specimens of different sizes and geometries

Specimen type	Specimen thickness (mm)	ASTM E1921 Master Curve transition temperature, T_0 (°C)	References
PCCVN*	10.0	-121	E. Lucon et al. [1]
0.35T C(T)**	8.9	-89 (single temperature approach for testing at -100°C) -76 (multi-temperature approach for testing at -100 and -120 °C)	R. Bonade et al. [2], R. Bondade [3], R. Bonade et al. [4]
0.87T C(T)	22.0	-78 (M=80 for constraint loss limit)	P. Mueller et al. [5]
PCCVN	10.0	-113	M. Serrano et al. [6]
KLST***	3.0	-99	
0.5T C(T)	12.7	-129	
0.2T C(T) or 0.4T C(T)	5.1 or 10.2	-112 (specimens machined from 8mm or 14mm plates) -95 (specimens machined from 25mm plates)	J. Rensman [7] E. Gaganidze [8]

*PCCVN: precracked Charpy v-notch specimen
**C(T): compact tension specimen; the number in front of "T" is specimen thickness in unit of inch
***KLST: one type of miniaturized Charpy specimen (from the German *Kleinstprobe*, or "small specimen")

Nonetheless, in order to exclude the specimen size effect on the measured fracture toughness of neutron irradiated Eurofer97, comparison of results obtained from larger size specimens with those from smaller size specimens after neutron irradiation is necessary, which is not practical and can be formidably expensive. However, limited literature results shown in Figure 2.3 [8] indicate that the transition fracture toughness of Eurofer97 obtained from different specimen sizes and geometries (5mm C(T), 10mm C(T), and 10mm PCCV) followed the similar irradiation embrittlement trend.

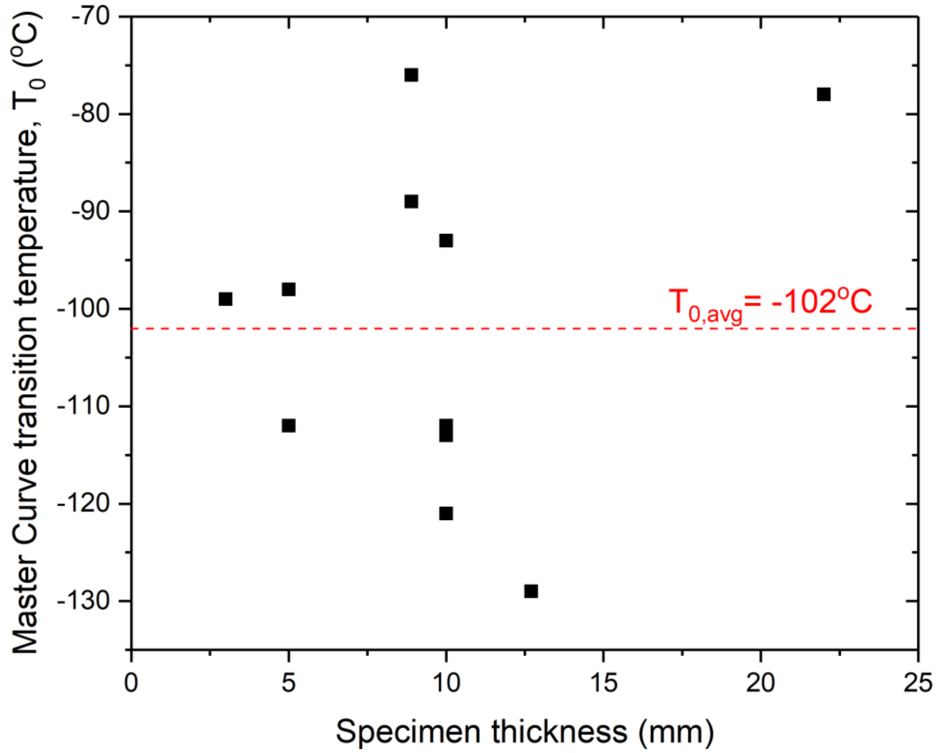


Figure 2.1 Effect of specimen thickness on the measured Master Curve transition temperature T_0 of Eurofer97

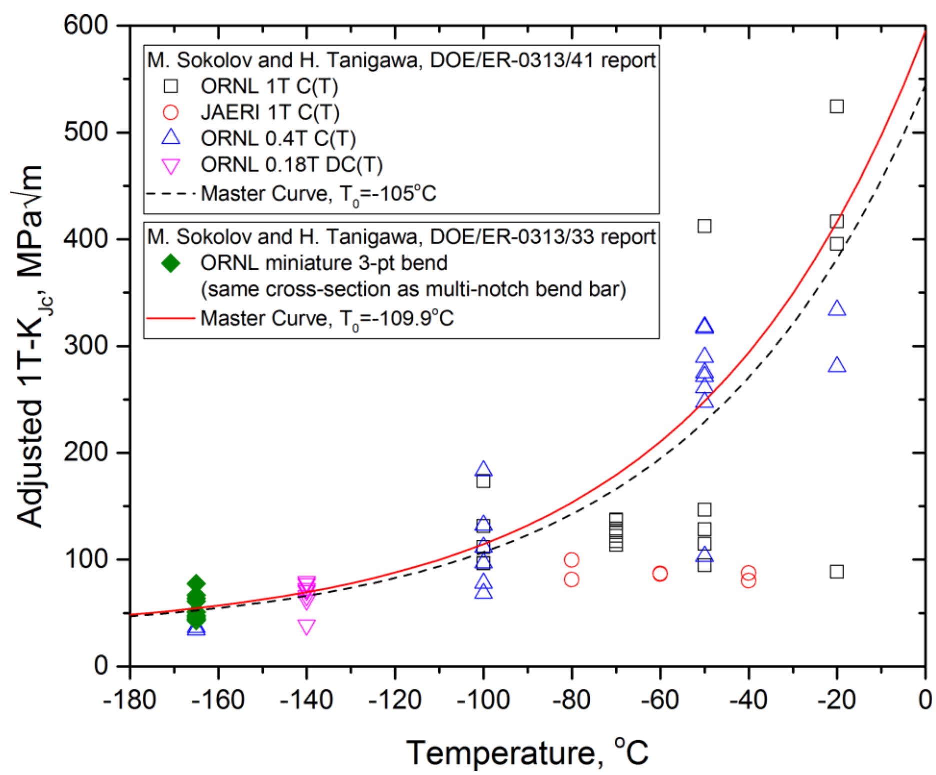


Figure 2.2 Comparison of fracture toughness results obtained from pre-cracked miniature 3-point bend specimens with those from larger size specimens

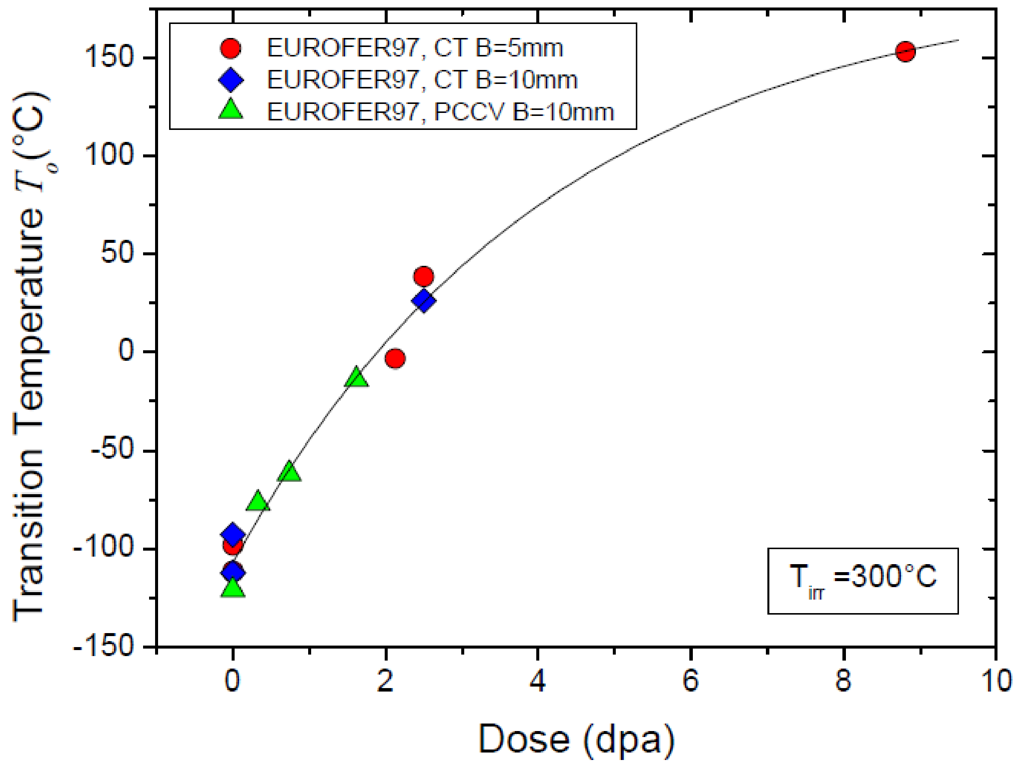


Figure 2.3 Fracture toughness transition temperature vs. irradiation dose on Eurofer97. CT specimens were machined from 8, 14 and 25 mm plates. PCCV specimens were machined from Ø=100mm bars. The specimen thicknesses are indicated in legend [8]

3. EXPERIMENTAL SETUP

In order to test neutron irradiated Eurofer97 pre-cracked M4CVN specimens shown in Figure 3.1, specialized testing devices are needed for the shielded hot cell facility. The testing devices should accommodate manipulator handling in the hot cell while overcoming potential challenges associated with testing small M4CVN specimens, such as aligning notches with the indenter and displacement gauge, accurate temperature control, etc. With these in mind, we have designed and fabricated dedicated testing devices as shown in Figure 3.2 and Figure 3.3.

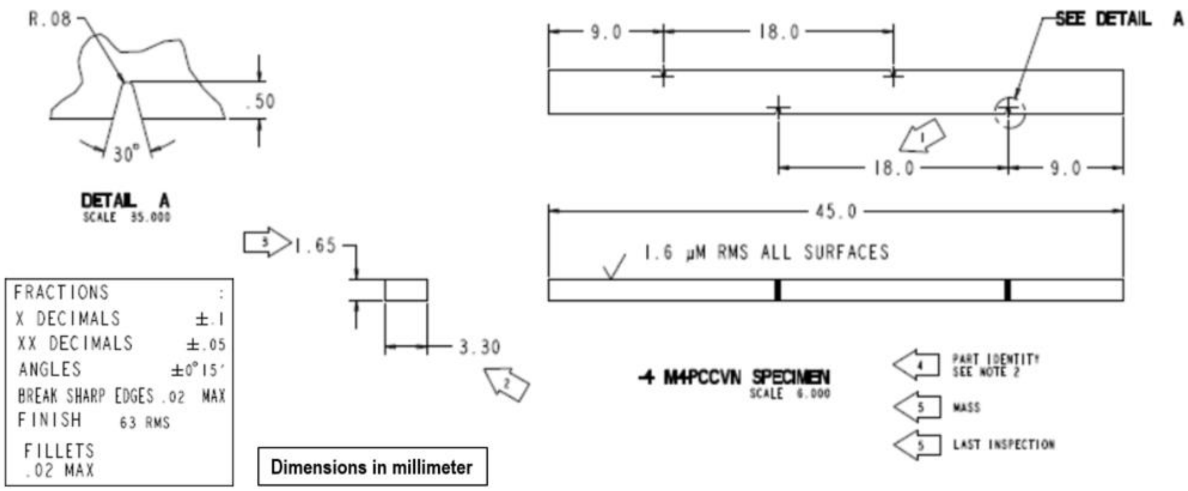


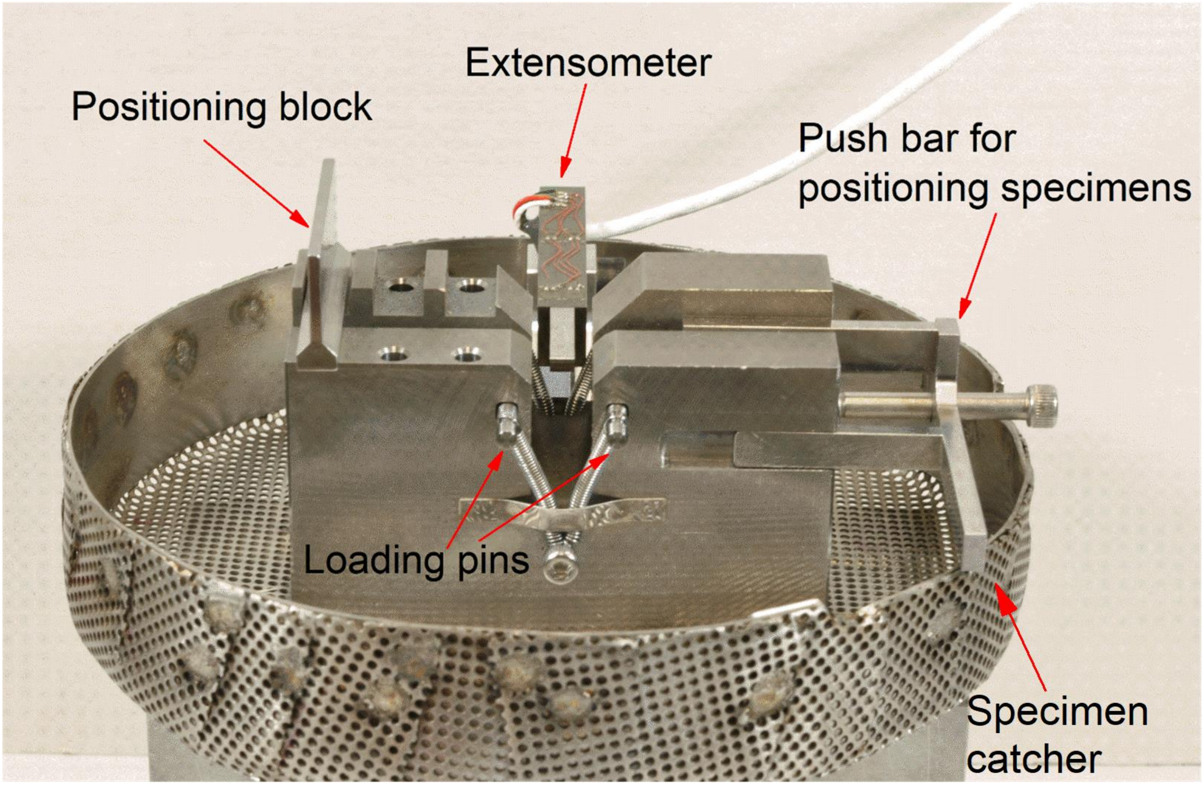
Figure 3.1 M4CVN specimen drawing

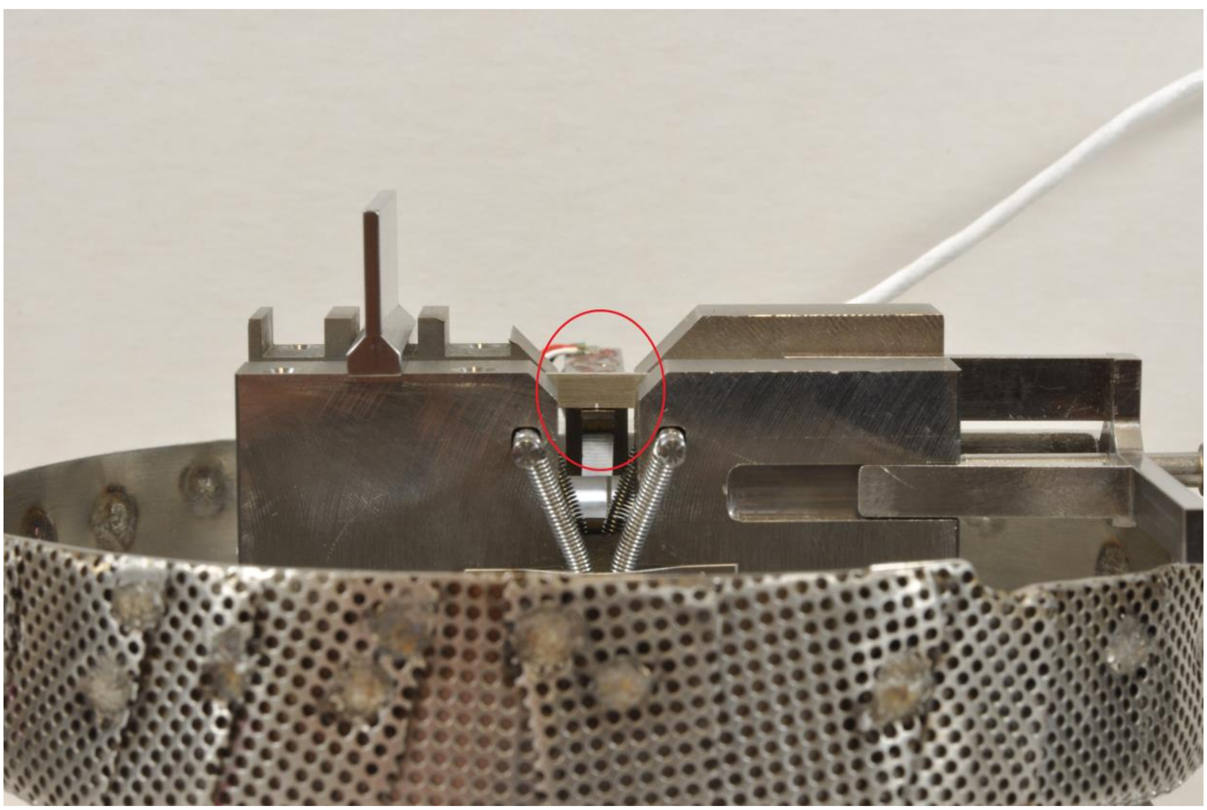
Figure 3.2 shows the environment chamber to be used for testing at elevated or low temperatures. The environment chamber was made of stainless steel and has vacuum insulation between its outer surface and inner surface. It also has feedthrough for both heated air and liquid nitrogen to cover a testing temperature range of -196 to ≥100 °C. Besides, the chamber is attached to a linear actuator at the bottom such that the chamber can be remotely moved up and down to facilitate specimen installation and removal.

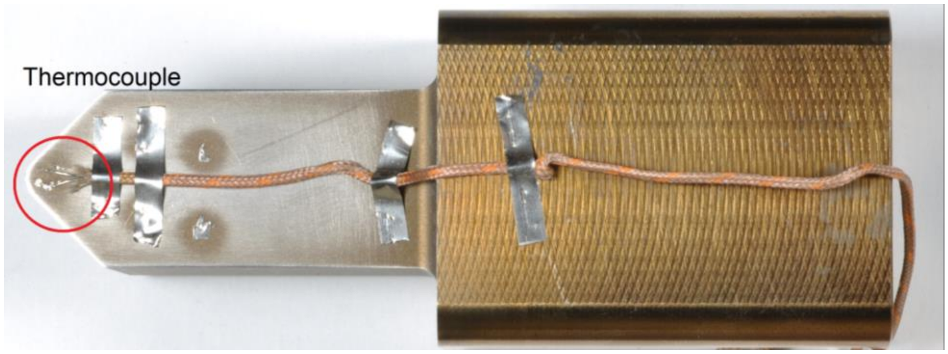
Figure 3.3a shows the M4CVN bend bar test fixture. The extensometer is used to measure the load line displacement of the specimen. The specimen catcher minimizes the chance of losing specimens during manipulator handling. The push bar can slide left and right and push the specimen against the positioning block such that the specimen notch is aligned at the correct test position as shown in Figure 3.3b. The top indenter shown in Figure 3.3c is used to load the specimen during testing. It has thermocouple wires spot welded to its front and back surface to measure test temperatures. Based on our recent testing experiences, temperature measurements from the thermocouple spot welded to the top indenter matched the temperature measurements from the thermocouple spot welded to a miniature multi-notch bend bar specimen for at least a temperature range of -160 to 80 °C. Due to the multi-notch design of M4CVN specimens, the tested notch has to cleave after a test so that the next notch can be positioned for testing. However, in case the specimen experiences ductile fracture and the tested notch does not cleave, the specimen breaking device shown in Figure 3.3d can be used to break the specimen at the tested notch location. The specimen breaking device employs the similar concept as the bend bar test fixture in Figure 3.3a where the positioning block and specimen place holder are used together to align the notch with the specimen break bar as shown in Figure 3.3e. Also, liquid nitrogen is fed into the breaking device to minimize the force and specimen deformation during the breaking process. Lastly, crack length measurements on the fracture surface are realized by using the specimen holder in Figure 3.3f. When one broken half specimen at each notch location is inserted into one of the four slots of the specimen holder, the fracture surface of the specimen is aligned at the same height as the calibration blocks marked as A, B, C, D in Figure 3.3f. Therefore, when the fracture surface is at right focus under an optical microscope, so are the calibration blocks. Then the known dimensions of the calibration blocks will be used to convert the pixel distance of the fracture surface image (shown in Figure 3.3f) to a physical length to measure the crack length.

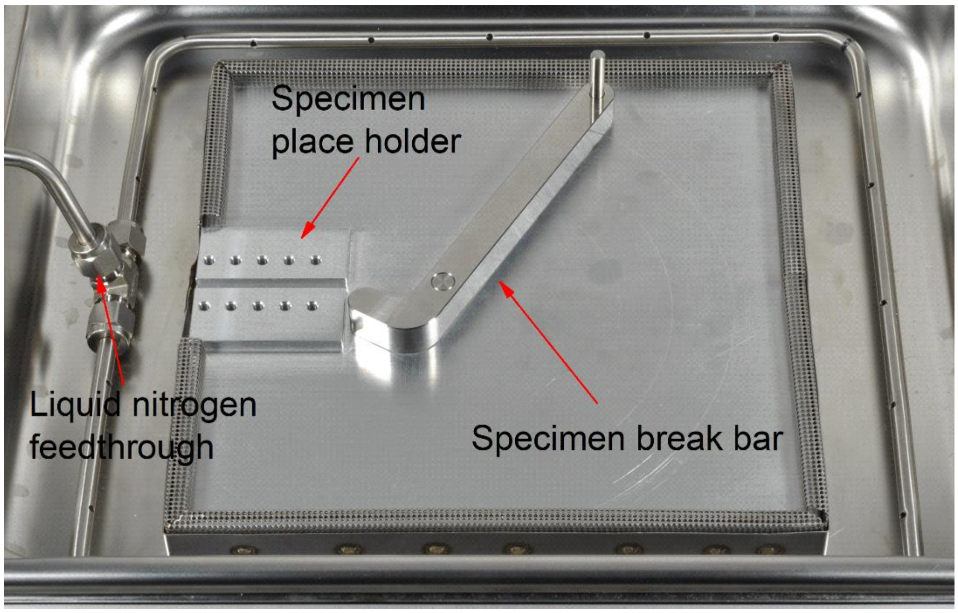
Recently, we have used the testing devices shown in Figure 3.2 and Figure 3.3 to test neutron irradiated F82H pre-cracked miniature multi-notch bend bar specimens (same size as M4CVN except for only 3 notches for the specimen) with great success. Considering the similarity of materials, specimens and the nature of tests, we believe the newly designed experimental setup can be used successfully in fracture toughness testing of Eurofer97 M4CVN specimens.

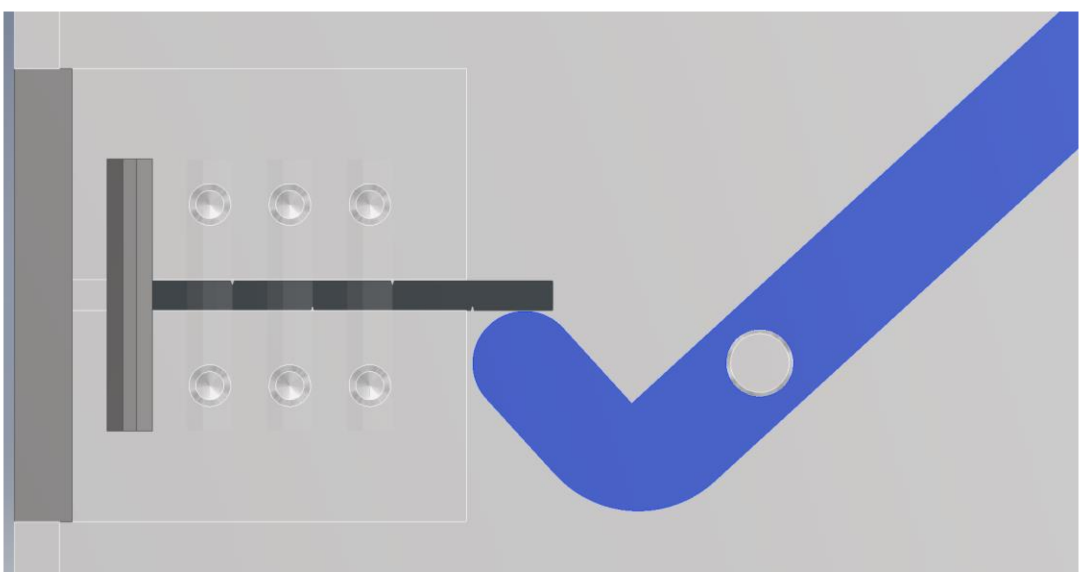
Figure 3.2 Environment chamber for testing at elevated or low temperatures

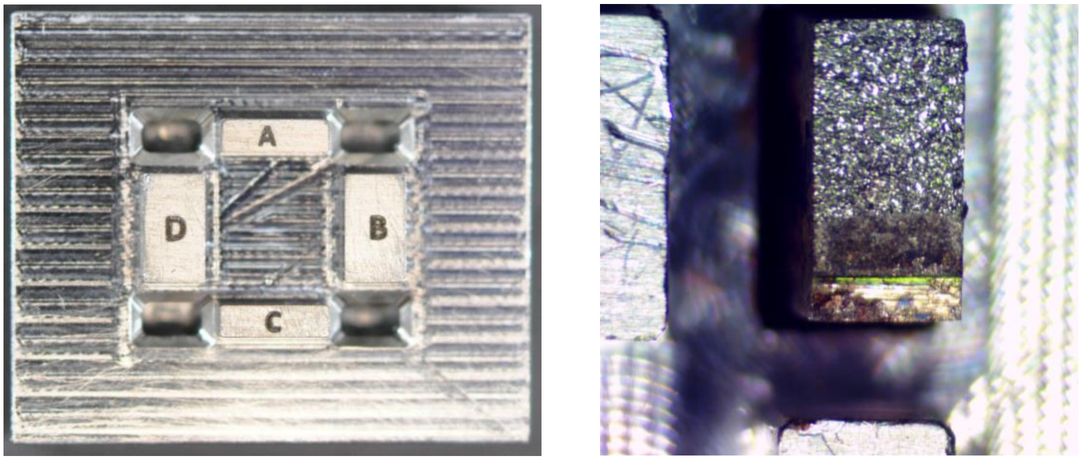

Extensometer
Positioning block
Push bar for
positioning specimens
Loading pins
Specimen
catcher
(a)


(b)


Thermocouple
(c)


Specimen place holder
Liquid nitrogen feedthrough
Specimen break bar
(d)


(e)



(f)

Figure 3.3 Experimental setup for testing neutron irradiated Eurofer97 pre-cracked M4CVN specimens. Bend bar test fixture in (a) and with M4CVN bend bar installed in (b), (c) top indenter with thermocouple wires spot welded, (d) specimen break device, (e) alignment of M4CVN specimen notch with the specimen break bar, and (f) specimen holder for fracture surface measurement

4. CONCLUSIONS

This report documents our feasibility study of using pre-cracked miniature multi-notch bend bar specimens (M4CVN) with a dimension of 45mm (length) x 3.3mm (width) x 1.65mm (thickness) to characterize the transition fracture toughness of Eurofer97 based on the ASTM E1921 Master Curve method. We draw the following conclusions for this report:

1. From literature survey results, we did not find any obvious specimen size effects on the measured fracture toughness of unirradiated Eurofer97.
2. In order to exclude the specimen size effect on the measured fracture toughness of neutron irradiated Eurofer97, comparison of results obtained from larger size specimens with those from smaller size specimens after neutron irradiation is necessary, which is not practical and can be formidably expensive. However, limited literature results indicate that the transition fracture toughness of Eurofer97 obtained from different specimen sizes and geometries followed the similar irradiation embrittlement trend.
3. We have designed and fabricated dedicated experimental setup to be used for testing neutron irradiated Eurofer97 pre-cracked M4CVN bend bars in the shielded hot cell facility. We believe the newly designed experimental setup can be used successfully in fracture toughness testing of Eurofer97 pre-cracked M4CVN specimens based on our recent testing experiences with neutron irradiated F82H pre-cracked miniature multi-notch bend bars, as both tests are similar in materials, specimen types, and the nature of tests.

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