ELASTIC-PLASTIC ANALYSIS OF THE SS-3 TENSILE SPECIMEN*

S. Majumdar (Argonne National Laboratory)

SUMMARY

Tensile tests of most irradiated specimens of vanadium alloys are conducted using the miniature SS-3 specimen which is not ASTM approved. Detailed elastic-plastic finite element analysis of the specimen was conducted to show that, as long as the ultimate to yield strength ratio is less than or equal to 1.25 (which is satisfied by many irradiated materials), the stress-plastic strain curve obtained by using such a specimen is representative of the true material behavior.

PROGRESS AND STATUS

Introduction

The SS-3 specimen has a much shorter gage length than typical ASTM-standard tensile specimens. More importantly, the solid area ratio between a section at the hole and that at the gage center is only 1.9 for the SS-3 specimen compared to 3 for typical ASTM standard specimens. This large area ratio in the ASTM standard specimen guarantees that there is little or no yielding in the grip section of the specimen during a tensile test. This is an important consideration for tests in which strain is not measured directly by an extensometer because errors will be introduced in the stress-strain curve as obtained from the measured load-displacement curve if large plastic strains occur outside the gage in the grip section. For this reason, if the ultimate to yield strength ratio of the test material is ≥1.9, the SS-3 specimen cannot be used to obtain the stress-strain curve. Even for materials with the ultimate to yield strength ratio < 1.9 (e.g., irradiated materials), there is a greater chance for yielding in the grip section of the SS-3 specimen than in an ASTM standard specimen, principally due to stress concentration effects. Elastic-plastic finite element analyses were conducted to estimate the effect of plastic yielding outside the gage section on the measured load-displacement (thus the stress-strain) curve.

Model for analysis

One quarter of the SS-3 (Fig. 1) specimen was analyzed using the finite element (4100 nodes and 3900 elements) program ANSYS with elastic-plastic material properties of irradiated (0.4 dpa) V-4Cr-4Ti at 420°C as reported in reference 1 (yield = 340 MPa, ultimate = 430 MPa and uniform elongation = 8%). The loading pin was assumed to be perfectly rigid and an initial radial clearance of 0.025 mm was assumed between the hole and the loading pin. Contact elements were used for modeling the transmission of load from the pin to the specimen. Thus, initially there was a line contact and the area of contact increased with increased loading. The analysis was carried out till 5% plastic strain (420 MPa) at the gage section.

* Work supported by U.S. Department of Energy, Office of Fusion Energy Research, under Contract W31-109-Eng-38.

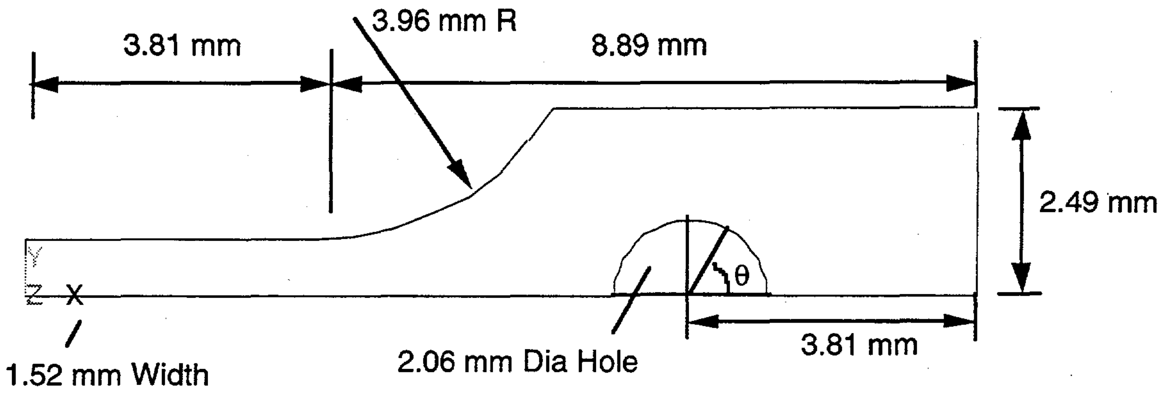


Fig.1 Geometry of specimen SS-3 (1/4 of specimen shown) with a thickness of 0.76 mm.

Results

A contour plot of tangential plastic strain near the hole at the final loading is shown in Fig. 2. There is about a 0.5% maximum plastic strain at the edge of the hole at the minimum cross-section of the specimen and a 1% plastic strain at the point of contact. However, note that the zones of tensile plastic strain are fully contained within elastic enclaves. The fact that the tensile plastic zone does not spread to the lateral free surface of the specimen is not surprising because the ultimate to yield ratio for this material is about 1.25 which is less than the area ratio 1.9.

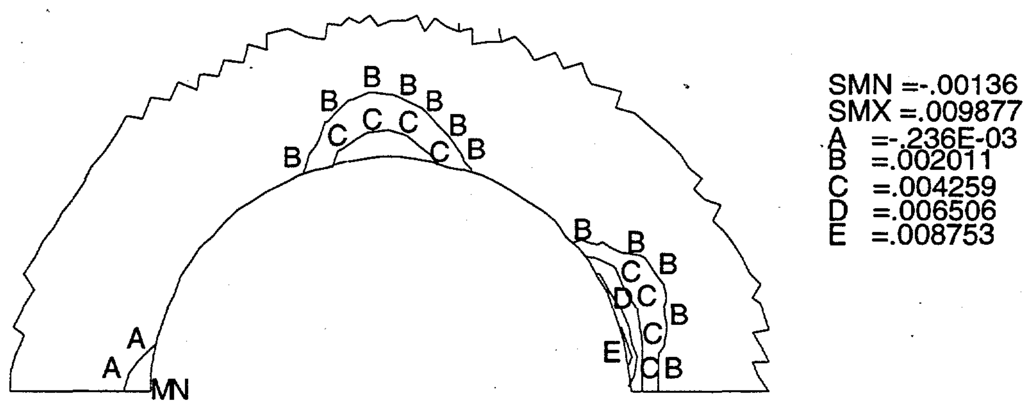
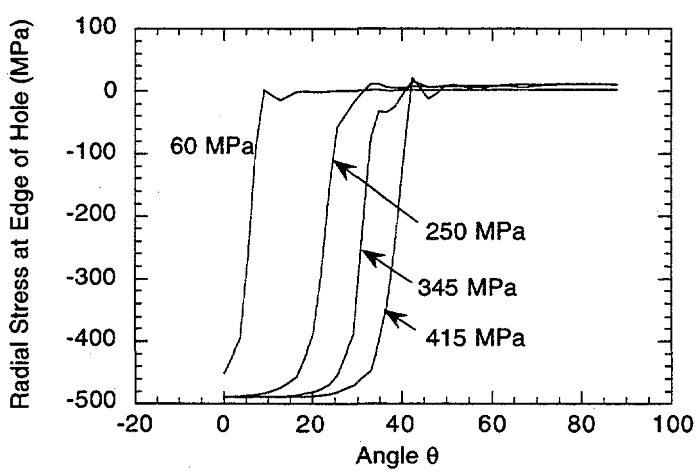


Fig. 2 Contours of constant hoop plastic strain near the hole for a gage section plastic strain of 0.05 (stress = 420 MPa).

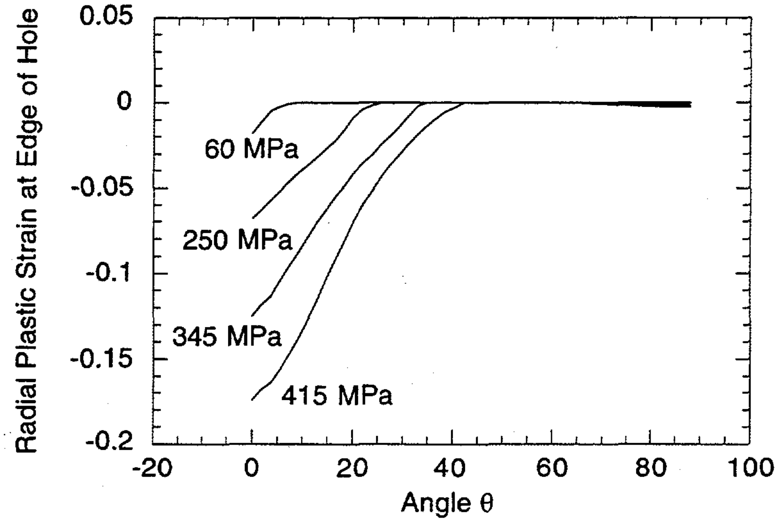
Angular variations (angle θ defined in Fig. 1) of the radial contact stress and radial plastic strain at the periphery of the hole at various gage section stress levels are shown in Figs. 3a and 3b, respectively. Compressive plastic yielding starts at the contact point from the very beginning and spreads with increased loading up to θ=40° at the final load level. Significant yielding occurs near the hole before there is any yielding at the gage section.

Significant yielding in the grip area could introduce nonlinearity in the load-displacement curve before the onset of yielding in the gage section and thus make the usefulness of the load-displacement curve questionable. To check this out, the load-displacement curve from the finite element analysis was used to derive the stress strain curve assuming that the displacements in the finite element analysis was used to derive the stress strain curve assuming that the displacements in the grip sections were negligible, i.e., the strain was obtained by dividing the total displacement at the loading pin by the gage length (7.62 mm.). A comparison between the derived and the input stress-strain curves, shown in Fig. 4a, shows that this assumption is incorrect because a significant component of the displacement comes from the grip section outside the gage.

Next, in accordance with usual experimental procedure, the stress-plastic strain curve was derived from the computed load displacement curve by first subtracting the elastic (initial linear part) displacement from the total displacement to obtain the plastic displacement and then attributing the plastic displacement to the uniform gage section only. The resulting stress-plastic strain curve is compared with the input stress-plastic strain curve in Fig. 4b. The good agreement between the two shows that in spite of significant yielding in the grip section, the stress-plastic strain curve for this material can be obtained from the load-displacement curve with good accuracy.

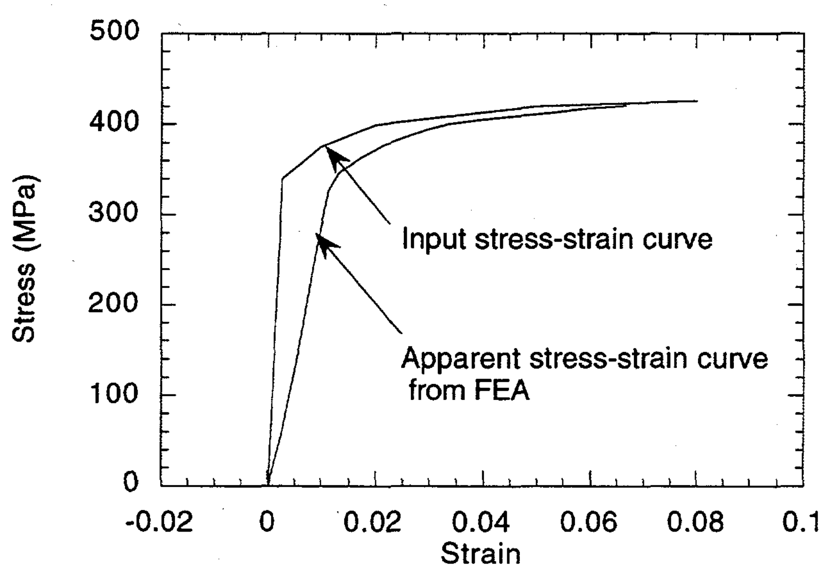


(a)

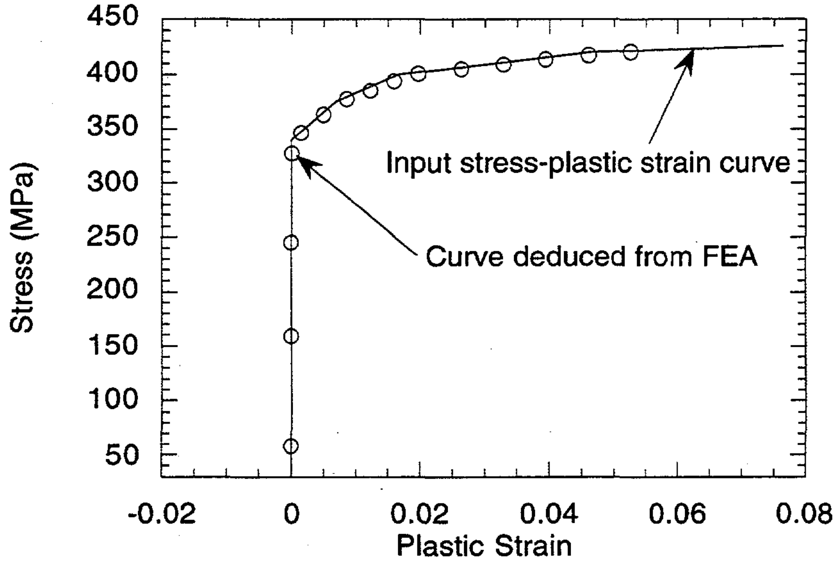


(b)

Fig. 3 Angular variations of radial (a) contact stress and (b) plastic strain at the edge of the hole for various values of gage section stress.



(a)



(b)

Fig. 4 Comparisons of (a) input stress-strain curve and apparent stress-strain curve derived from load-displacement curve by FEA and (b) input stress-plastic strain curve and stress-plastic strain curve derived from computed load-displacement curve by FEA.

Discussions and Conclusions

A detailed elastic-plastic finite element analysis of the SS-3 specimen using stress-strain curve for irradiated V-4Cr-4Ti at 420°C showed that large compressive plastic strains occurred at the contact area between the loading pin and the specimen. Significant tensile yielding also occurred at the periphery of the hole 90° away from the contact zone due to stress concentration effects. However for materials with ultimate to yield ratio of 1.25, this plastic zone was fully contained within an elastic enclave. As a result, the contributions of these plastic strains to the plastic displacement of the loading pin were small compared to those from the gage section. Thus, the stress-plastic strain curve for this material can be derived from the load-displacement curve with good accuracy. However, note that it was assumed that the material at the contact area continued to carry high compressive stress (ultimate stress) with high accumulated compressive plastic strain (much greater than uniform elongation) without cracking. If the compressive ductility (or the crushing strength) of the material is reduced by irradiation significantly and the contact area experiences cracking, non-linearity in the load-displacement curve may occur before the gage section reaches yield, thus introducing some uncertainty in the determination of the yield stress.

The SS-3 specimen is acceptable for irradiated materials for which the ultimate to yield strength ratio is low (≤1.25). However, unless an extensometer is used to measure the gage section strain directly, only the stress-plastic strain curve can be obtained - the full stress-strain curve cannot be obtained.

REFERENCE

1. Thermophysical and mechanical properties for V-(4-5%)Cr-(4-5%)Ti Alloys, draft report by S. J. Zinkle, Oak Ridge National Laboratory, May 1, 1998.