# EFFECT OF SUSTAINED LOAD AND LOW LOADING RATE ON THE TEARING RESISTANCE OF A PRESSURE VESSEL STEEL

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The purpose of this study was to evaluate the possible degradation of the fracture toughness parameters in PWR service conditions by various factors such as loading rate and pressurized hot water environment. For that, tests on CT specimens with sustained load and low loading rates were made on a SA 508C13 steel with high sulphur content, with the aim to have maximum of susceptibility. The results show that the usual J-R curve determinations in air at higher loading rate are applicable to the crack initiation and propagation in service conditions.

## INTRODUCTION

The pressure vessel steels (16 MND 5, SA 508 Cl 3, SA 533 gr B Cl 1) used in the primary circuit exhibit a toughness decrease when the temperature rises from 100 to 200-250 °C (1-4), reaching a minimum then the toughness increases again. The position on the temperature scale of this minimum is a function of the loading rate, in accordance with a strain aging phenomena.The results shownin figure 1, displayed a minima of $K_{JC}$ value significantly lower for the low loading rate tests than for the classical rate tests. Therefore, it is important to precise the values and the position of the minima, with the objective of exploitation of current testings for different service loading conditions. In addition, an increase of the sulphur level induces a reduction of toughness in the transverse direction. Another element of reflexion is constituted by the significant increase of fatigue crack growth rate in PWR environment for high sulphur contents in P.V. steels. For all these reasons, it is possible to suspect an influence of the low loading rate in PWR environment on the toughness of a high sulphur material.

The aim of this study is therefore to examine on a steel selected for its high sulphur content, with a moderate initial tearing modulus, the influence of the loading rate at different temperatures and of the primary water environment on the toughness $J_{1C}$ and on the J-Resistance curves (J-Δa). The lowest loading rates are selected in conjunction with the lowest rate of transients leading to important

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loadings ($K_I > 100$ MPa $\sqrt{m}$) in the temperature range of interest (100 to 300 °C). This study is completed by long sustained loading times at 290 °C on 1T. and 2T. CT at sollicitation levels corresponding to $J_{1C}$ or over. The influence of PWR environment on the J-R curve is studied on CT specimens using the interrupted test method.

## MATERIAL PROPERTIES

The material selected for its high sulphur content is coming from a primary coolant nozzle of PWR vessel (in a SA 508 Cl 3 steel). The properties are determined in the transverse direction (TS for CT and Charpy V specimens) on different acceptance tests rings for the nozzles extracted from the same heat.

In all cases, the sulphur content is found to be of 0.014% in weight, but the Charpy impact data present a large scatter between 74 and 101 J. Fractographic examinations indicate a good agreement between the energy level and the local content of inclusions.

Tensile properties are determined at two loading rates for different temperatures. In the case of the low loading rate, the ultimate tensile stress starts to increase and the yield stress stabilizes at 155 °C (Fig.2). This behavior is typical of a dynamic strain aging sensitivity. This phenomenon appears more for lower temperatures than the loading rate is smaller.

## INFLUENCE OF LOADING RATE AND TEMPERATURE ON THE J-R CURVES

Tests are conducted at different loading rates and temperatures using 1T and 2T CT specimens. The J resistance curves are established by the unloading compliance method. For conventional opening test rates of the specimens (0.4 to 1 mm/mn), $J_{1C}$ is lowering when the temperature increases (Fig.3). The influence of the loading rate is relatively small. Morever for low rates of 1.6 and 4.5 $10^{-2}$ $kJm^{-2}$ $s^{-1}$ corresponding to slow transient sollicitations, a beneficial effect induced by dynamic strain aging is observed. For these low rates, the decrease of $J_{1C}$ with the increase of temperature is stopped at about 150 °C and the values are rather constant from 150 to 290 °C. This is the result of dynamic strain aging on the behavior of the material : stabilization of Y.S.and increase of U.T.S. which compensate a slow decrease of the ductility. These results are in good accordance with those obtained by AMAR et al. (3) and PICKLES et al. (4) but they conflict with those of OSTENSSON (1) who obtained a minimum value of $J_{1C}$ for the lowest loading rates.

An important consequence of the present work is the fact that the value of toughness determined at a conventional loading rate is conservative for the lowest loading rates. The minimun of initiation toughness $J_{1C}$ is obtained near the operating temperature (250-290 °C). The tearing resistance dJ/da is lowering up to 150 °C and after that, it is rather constant with a mean value of about 55 MPa (Fig. 4). The moderate evolutions of dJ/da observed may be in relation with the low initial value of the tearing modulus, and due to the scatter of results it is impossible to demonstrate any significant effect of the loading rate.

## J-Δa TESTS IN PWR ENVIRONMENT

As shown by fatigue crack growth rate studies (5), high sulplur materials appear to be sensitive to PWR primary water environment. CT specimens are monotonicaly loaded at a low strain rate of $5.10^{-3}$ mm/mn, at 290 °C under a pressure of 140 bars to determine the J-Δa resistance curve using the interrupted test method. Considering the scatter of results, it is difficult to determine the J-Δa curve. However, the tests in PWR environment are in the scatter band of results obtained in air (Fig. 5).

It is possible to conclude that for tests at 290 to 300 °C, and for a range of loading rates between $10^{-3}$ and 1 mm/mn, J-Δa curves are not appreciably affected by the rate and the environment. This is in accordance with the results of GIBSON (6) on a same type of steel. On the other hand, in BWR environment, KONDO et al. (7) observed a decrease of $J_{IC}$ and dJ/da more than 20 % for a loading rate of $2.10^{-3}$ mm/mn.

## EFFECT OF SUSTAINED LOAD OR DISPLACEMENT AT 290 °C

The objective is to examine if sustained load or displacement tests are susceptible to induce stable or unstable crack growth at 290 °C. For that sustained load tests are conducted during different times ranging from 4 h to 100 h, and at sollicitation levels corresponding to $J_{IC}$ up to the limit load of the specimens. A limited amount of tests with sustained displacements are also conducted before and after the maximum of the loading curve.

For a sustained load over $J_{IC}$, a limited stable crack growth of about 0.3 mm is observed during the first minutes of the tests followed by a complete stability. For example, Fig. 6 shows tests after 4 h of sustained load. It is obvious that with all the data in the scatter band of conventional tests results no noticeable effect of the sustained load can be detected. These results are in accordance with a study of T. INGHAM (8).

In the same manner, no crack extension is observed under sustained displacement (Fig. 6), but only a logarithmic relaxation of the load of about 6%.

## GENERAL CONCLUSIONS

The essential conclusions issued of the present study on the effect of service conditions (loading rate, sustained loading, temperature, environment) on the J-Resistance curves of a pressure vessel steel SA 508 Cl 3 having a high sulphur content (0.014 %) are the following

- A dynamic strain aging phenomena in the interval of 150 to 300 °C, function of the loading rate is obvious. A consequence is the stabilization of the Y.S. and an increase of the U.T.S.

- For the classical loading rate the initiation toughness $J_{IC}$ decreases when the temperature increases and reaches a value of 87 kJ/m$^2$ at 290 °C.

- For a loading rate 100 times higher,less corresponding to important service transients, the evolution with the temperature is similar in a first part, but $J_{IC}$ keeps a rather constant value of 100 $kJ/m^2$ between 150 and 290 °C. This is attributed to the effect of dynamic strain aging on the tensile properties of the steel.

- The low loading rate tests in PWR environment do not show any significant difference with tests in air at 290 °C.
- Sustained loadings over $J_{IC}$ produce only a slight stable crack growth (0.3 mm) during the first minutes of the test.

- The usual J-R curve determinations in air at a higher loading rate are applicable to the crack initiation and propagation in service conditions.

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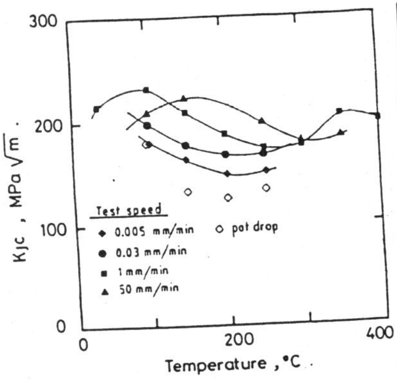


Fig. 1 - Evolution of $K_{JC}$ with the temperature for different loading rates /_1_/

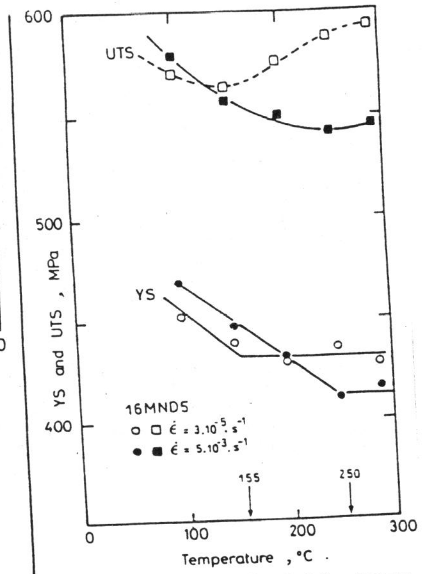


Fig. 2 - Evolution of yield stress and ultimate stress with the temperature for two loading rates

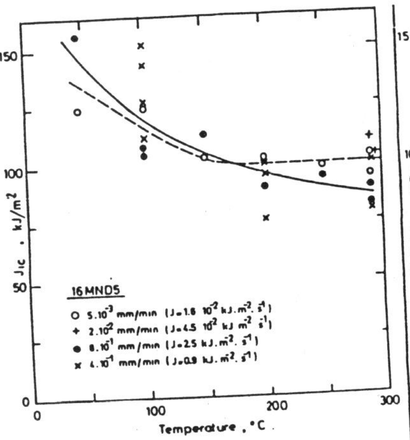


Fig. 3 - Variation of $J_{1C}$ with temperature and loading rate

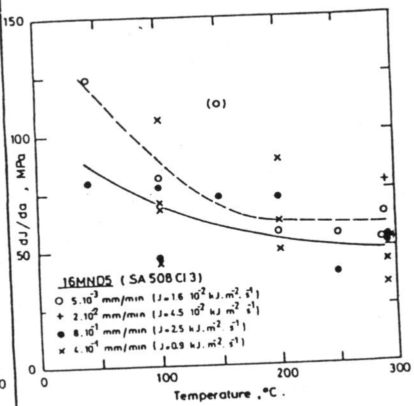


Fig. 4 - Evolution of dJ/da with the temperature for different loading rates

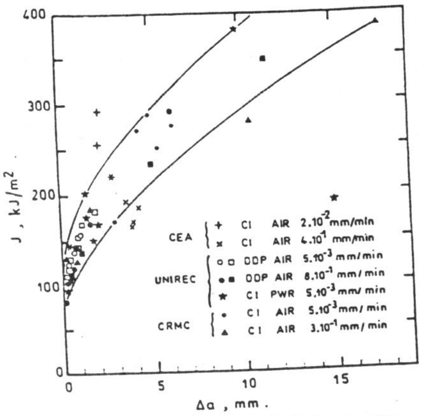


Fig. 5 - Comparison of J-Δa tests at 290 °C in air and PWR environment

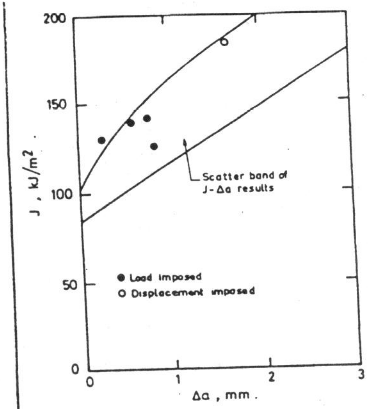


Fig. 6 - Comparison of J values after 4 h sustained loading with the scatter band of conventional results