Dynamic tensile tests with superimposed ultrasonic oscillations applied to stainless steel type 321

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ABSTRACT

The purpose of this study is to appraise whether or not the phenomenon of "acoustic softening" due to ultrasonic oscillations is significant for stainless steel type 321 at high strain rates and room temperature. A drastic effect might be relevant in explaining discrepancies in a code validation exercise for HCDA containment codes. A hydro-pneumatic test apparatus was developed which allows dynamic tensile testing at room temperature with and without superimposed ultrasonic oscillations. The experimental set-up is described, the major experimental results, and some modelling aspects are presented, and their relevance for the code validation exercise is indicated.

1. INTRODUCTION

A number of different computer codes, which analyze the mechanical consequences of a Hypothetical Core Disruptive Accident in a Fast Breeder Reactor, have been subjected to extensive assessment by comparison of computational results with measurements carried out for explosion tests (COde VAlidation experiments) performed on water-filled vessels /1, 2/. The comparison has shown that the computation underestimates systematically the measured strains. Further, high-frequency pressure oscillations (10 to 50 kHz) occur at the vessel walls which are not predicted by the calculation. Sensitivity calculations /2/ have shown that the underestimations continue as a tendency or the variations do not provide a consistent agreement in the strains and loads. When searching for an explanation, it was suggested that the observed pressure oscillations may be related to small stress oscillations in the vessel wall, which possibly may produce an "acoustic softening" of the material /2/. This softening phenomenon has been observed at low rates of strain for various metals: Ultrasonic oscillations superimposed on a specimen in a tensile test may lead to a reduction of the mean stress necessary to maintain the prescribed average rate of deformation. This reduction may be rather large /3-6/ or small, i.e. roughly equal to the stress amplitude, e.g. /7-9/.

According to the authors' knowledge experiments have not been performed at high mean deformation rates comparable to those of the COVA tests. Only if a drastic "acoustic softening" is present at high strain rates, it may possibly exert an influence in the fast COVA tests. There-

fore, dynamic tensile tests were performed with superimposed ultrasonic oscillations and under conditions which are comparable with those prevailing in the COVA tests. These experiments were carried out with a newly developed hydro-pneumatic, high-velocity tensile device for mean strain rates between 3×10^{-5} s^{-1} and 30 s^{-1}, with and without superposition of high frequency (40 kHz) oscillations with a strain amplitude of 0.2 °/oo at the maximum /10/.

2. THEORIES ON THE "ACOUSTIC SOFTENING" EFFECT

The explanation of the "acoustic softening" effect at low rates of strain appears to be a matter of controversy. Several models have been suggested.

The theory of "local heating" suggests that localized heating occurs due to internal friction in regions around dislocations or grain boundaries when ultrasonic stress waves propagate through the metal /5/. Thus the resistance against plastic flow is decreased, analogous to that observed at high temperatures, although macroscopically no heating can be observed.

The theories of the "superposition mechanism" explain the "acoustic softening" effect by the fact that for nonlinear material behavior the maximum stress during a load cycle determines the plastic deformation, whereas the load measurement yields the mean stress, i.e. a lower value. Some authors /7-9/ state that a rate-independent elastic-plastic material model with perfectly elastic unloading suffices to describe the phenomenon. Assume that an oscillatory strain component with amplitude ε_a and circular frequency ω is superimposed on a mean strain rate $\dot{\varepsilon}_m$ = const. For the rate-independent model the stress reduction $\Delta\sigma$, which is the difference between the flow stress without insonation and the temporal average of the stress during an ultrasound period, is found /10/ to be a linear function of $\sigma_a = E\varepsilon_a$ and E_t/E but is nonlinearly dependent on $\eta = \dot{\varepsilon}_m/\omega\varepsilon_a$, the relative strain rate; here E and E_t are Young's modulus and the current tangent modulus. This relation is plotted in Fig. 4. It is seen that with increasing strain rate $\dot{\varepsilon}_m$ the stress reduction decreases and disappears at $\eta = 1$, where unloading no longer occurs. At low strain rates $\Delta\sigma$ approximates the value of the elastic stress amplitude $E\varepsilon_a$.

In a similar way the non-linear behaviour of a visco-plastic material leads to an apparent reduction in stress /12/. Accounting for small overstresses and elastic material response the constitutive equation is given by

$$\dot{\varepsilon} = \dot{\sigma}/E + D(\exp[B(\sigma-\sigma_o)] - 1) \qquad (1)$$

where D and B are material parameters and σ_o is the "static yield stress" below which the response is purely elastic. Assuming that the ultrasound induces a stress amplitude σ_a the stress reduction $\Delta\sigma$ may be approximated for small average strain rates and large frequencies by /10/

$$\Delta\sigma = B^{-1}\ln\phi, \quad \phi = \sum_{m=0}^{\infty}\left[(B\sigma_a/2)^m/m!\right]^2. \qquad (2)$$

Obviously, under the above assumptions $\Delta\sigma$ is independent of the average strain rate and the frequency. It may be shown that the stress reduction is smaller than the stress amplitude. However, the two quantities approach each other with increasing value σ_a. Further, this model allows for a time dependent stress transition when ultrasound is

switched on and off; this transition is depending on the mean strain rate $\dot{\varepsilon}_m$ /10/.

3. EXPERIMENTAL TECHNIQUE AND PROGRAM

The schematic experimental set-up is shown in Fig. 6. In order to be able to conduct fast experiments, the whole experimental facility has been given a rather compact design. The specimen have an active length of only 10 mm, and they have long thin shoulders so that ultrasound can be well introduced. The ultrasound generation and the recording of the measurement data are triggered when the bursting disk (glass hat) is destroyed. Then oil flows through a calibrated orifice and releases the piston which is accelerated by compressed nitrogen. After a short transient phase (0.5 ms) an almost constant piston velocity is obtained. The ultrasonic oscillations are generated by two piezo ceramic disks fed with an alternating voltage. A transformer horn transmits the waves into the specimen and amplifies them. After about 1.5 ms a stationary standing wave is formed (Fig. 6). The specimen is positioned in the range of maximum stress. So a nearly homogeneous stress condition prevails in the specimen. In all experiments the strain is measured both on the specimen and at the linear elastic horn. The measurement performed at the horn (load cell) allows to draw conclusions with regard to the average stress acting in the specimen. The ultrasonic stress oscillations in the specimen can be estimated from the strain oscillation at the specimen or at the load cell.

The specimens were fabricated from a stainless steel sheet (type AISI 321, thickness 1.7 mm) which belonged to the same batch as the sheets used for the COVA vessels. Several tests were performed at each of five different strain rates between 3×10^{-5} and 30 s^{-1} (COVA tests: $\dot{\varepsilon}_m \sim 25\ s^{-1}$). The dynamic tensile tests were performed without and with ultrasonic insonation. Only one ultrasonic frequency was applied which corresponds to a resonance of the system ($\sim$ 37.5 kHz). In the slow tests (average rate less than $3 \times 10^{-3}\ s^{-1}$) insonation was applied but shortly and intermittently because a long exposure destroys the strain gages and heats up the specimen. In the other experiments insonation was continuously.

4. EXPERIMENTAL RESULTS

Figure 1 shows the flow stress in tensile tests without insonation as a function of the current strain rate with the strain as a parameter. In the half-logarithmic representation the frequently found linear strain rate dependence is observed. Besides these new measurements, the experimental results already available for the same material are shown, too. Within the range of material data scatter good agreement is obtained with the UK data /12/ and with the JRC Ispra data /13/ for small strains (0.1 %). For large strains the flow stresses of the JRC Ispra data exceed the new data by about 20 %.

Figure 2 shows the stress-strain plot of a slow tensile test with intermittent insonation. If, after the yield point has been surpassed, ultrasound is switched on, the flow stress drops to a somewhat lower value and increases again after ultrasound has been switched off. These stress transitions are gradual /10/.

When continuous insonation is applied again a small stress reduction is observed. Similar to the experiments without insonation, the re-

duced flow stress is plotted versus the strain rate (Fig. 3), including also experiments with intermittent insonation which have been carried out up to a strain rate of 3×10^{-3} s^{-1}. The regression lines for low strain rates exhibit the tendency towards the "acoustic softening" effect. Independet of the magnitude of the deformation, this reduction in stress decreases with increasing strain rate.

Taking into account the differences in strain amplitudes ε_a, Fig. 4 shows the relative stress reduction $\Delta\sigma/E\varepsilon_a$ versus the relative strain rate η. The relative stress reduction undergoes but little variations at low relative strain rates, but it decreases and disappears completely in experiments involving higher rates.

5. COMPARISON WITH THE TWO SUPERPOSITION MODELS

Within the scatter of the measured data the rate-independent model reflects well the strong decrease of the relative reduction in stress above a relative strain rate of 10^{-2} (Fig. 4). On the other hand, in the range of small relative strain rates the rate-independent material model clearly overestimates the measured relative stress reduction.

To predict the stress reduction of the visco-plastic model the parameter B was determined by fitting relation (1) to the results in Fig. 1. A value of $B = 0.2$ mm^2 N^{-1} was found which is nearly independent of the plastic strain. Figure 5 shows the normalized stress reduction $B\Delta\sigma$ according to the two superposition models for slow tensile tests and according to the measurements. For the visco-plastic model it may be shown that for small average strain rates less than 6 s^{-1} imposed oscillations cause mainly elastic deformations. Therefore, Fig. 5 contains only measurements involving rates less than 6 s^{-1}. Despite the considerable scatter of the measured data, the visco-plastic model is in better agreement with the measured stress reduction at low average rates of strain ($\dot{\varepsilon}_m \leq 6$ s^{-1}) than the rate-independent model. The quality of the visco-plastic model in very fast tensile tests ($\dot{\varepsilon}_m > 6$ s^{-1}) involving insonation has not been investigated.

It is fairly obvious that a rate-independent model cannot provide a description of the stress transition during switch-on and off of the ultrasound. The situation is different with an elastic-viscoplastic model. The calculations with this model demonstrate a reasonable good agreement with the measurement at different average strain rates /10/.

6. CONCLUSIONS

For small strain rates in the tensile tests without insonation the new measurements of the flow stress agree well with former results obtained by the UKAEA. However, for high strain rates the flow stresses are about 20 % smaller compared to the JRC Ispra data. In the experiments involving ultrasonic oscillations only a small stress reduction is recorded which at low strain rates is about half the amount of the elastic stress amplitude. At larger strain rates the stress reduction decreases and ultimately, scatters around the value zero. During switching on and off the ultrasound a stress transition is observed.

When ultrasonic oscillations are superimposed upon low rate stretching the rate-independent elastic-plastic material model predicts a stress reduction which is too large by a factor of approximately two; but the disappearance of the stress reduction at high strain rates is rather well reflected. The elastic-viscoplastic model allows for a better des-

cription at low strain rates. Further, it gives an interpretation of the strain rate dependent stress transition associated with intermittend insonation.

The "acoustic softening" effect for AISI 321 is far too small to be of significance for the COVA validation exercise and, in addition, it does not require a new modelling of the material behaviour. Further, previous sensitivity studies /2/ associated with the COVA tests clearly showed that a mere reduction of the yield stress in the COVA calculations does not give a consistent agreement in observed vessel strains and loads. Therefore, the discrepancies in the flow stress measurements at high strain rates does not suffice to explain the observed underestimation of vessel strains in the COVA tests.

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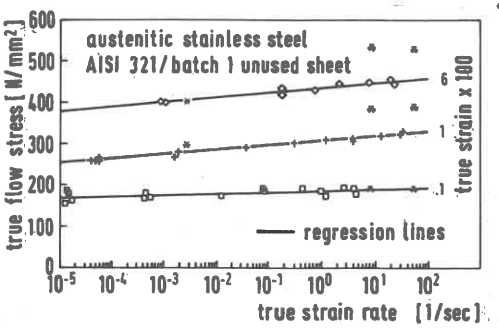

Fig.1 Flow stress versus strain rate without insonation (* UK data, ♣J R C Ispra data)

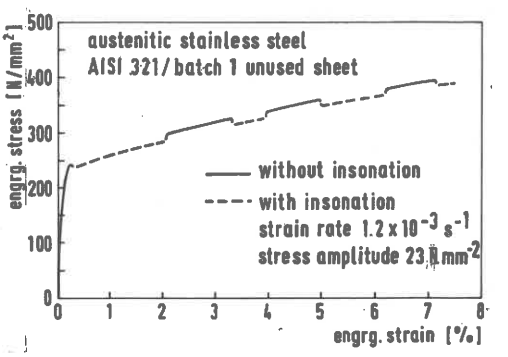

Fig.2 Stress-strain curve with intermittent insonation

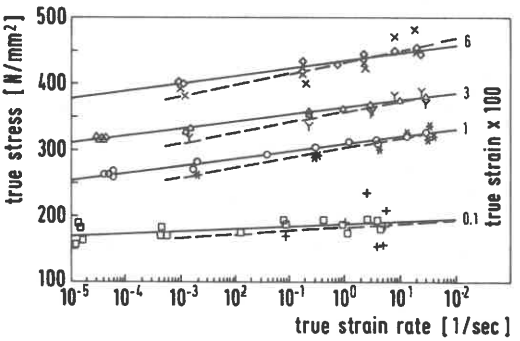

Fig.3 Flow stress versus strain rate with (- - -) and without (——) insonation

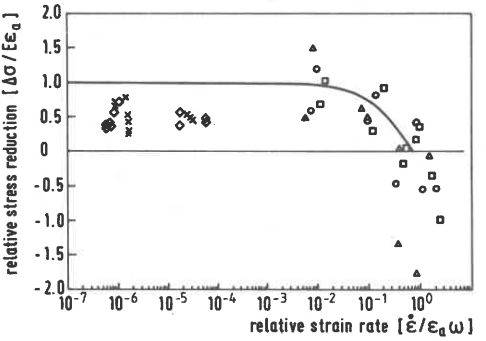

Fig.4 Relative stress reduction versus relative strain rate; experiment and rate-independent el.-pl. theory (——)

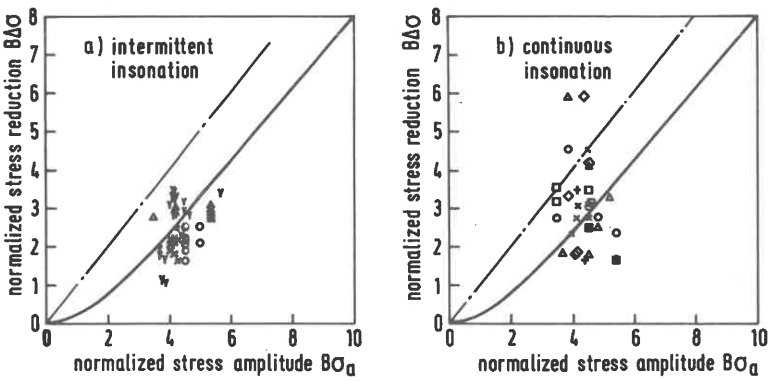

Fig. 5 Comparison of measured normalized stress reductions with theoretical results for various normalized stress amplitudes; (-·-) rate-independent, (——) el.-viscoplastic theory

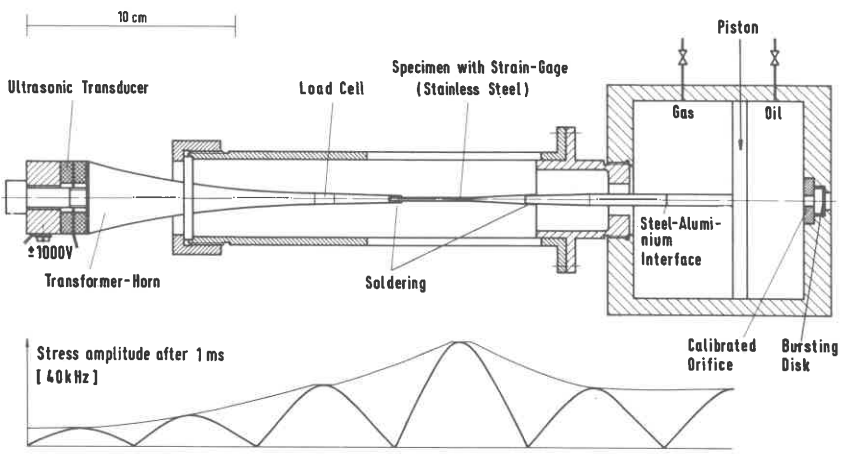

Fig.6 Schematic sketch of the experimental set-up (above). Standing ultrasonic waves in the set-up (below)