Ultrasonic Measurement of Creep Damage in Pipe

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ABSTRACT

Creep damage in the form of grain boundary cavities is shown to decrease the ultrasonic wave velocity in ferritic steel. Earlier experiments have shown the same effect in commercially pure copper, in a Fe-Ni-Cr alloy casting, and in austenitic stainless steel. Rupture due to creep damage is normally hard to predict due to its brittle character. A non destructive technique is therefore highly demanded. It is shown how influence on ultrasonic velocity due to damage may be separated from other metallurgical effects in testing of pipe.

KEYWORDS

Creep damage; Ultrasonic velocity; Non destructive technique

INTRODUCTION

Components working at elevated temperatures are known to deteriorate due to a number of reasons, e.g. various types of degradation of the microstructure, corrosion, creep, and creep damage, cf. e.g. Ashby and Dyson (1984). The term creep-damage will here allude to the effects of nucleation and growth of small grain boundary cavities. Such voids are found to be uniformly distributed in homogeneously stressed regions and to grow mainly on grain boundaries normal to the main tensile direction, cf. e.g. Riedel (1987). High temperature and low stress are often desirable working conditions but they also promote the influence of voids over the effect of creep deformation. The material 'rottens' and fractures in a brittle manner when the voids interact to form a crack. Hence, non destructive techniques to monitor the remnant life are highly demanded especially since many high temperature plants now approach their design life.

A method to monitor the level of damage in creep damaged commercially pure copper was proposed by Bråthe (1978). The idea is to measure the ultrasonic wave velocity and to relate it to the level of damage. It was shown experimentally that the ultrasonic velocity had decreased substantially in creep ruptured specimens. Later Stigh et al (1983) and Stigh (1987) found the same effect in an austenitic stainless steel and in a Fe-Cr-Ni alloy casting. The latter also related, theoretically, the level of damage to the decrease of the ultrasonic velocity.

One of the main difficulties in testing this method is to get access to creep damaged components. The purpose of the present paper is to show that creep damaged ferritic steel also employs the same relation between creep damage and ultrasonic velocity. In ferritic steel one can expect some difficulties due to the structural changes that take place at high temperatures, i.e. development of bainite and martensite. These are known to influence the ultrasonic velocity (Krautkrämer 1969). It is shown here how these effects may be separated from the creep damage effect in testing of pipe.

Continuum mechanical theories to treat the deteriorating effects of the voids have been developed originating with works by Kachanov (1958) and Rabotnov (1963), the purpose being to formulate constitutive equations that describe the process. This is now denoted Continuum Damage Mechanics (CDM), cf. Janson and Hult (1977). For recent reviews cf. Krajcinovic (1984), Lemaitre (1984), Murakami (1987) and Hult (1988). The idea is to introduce a new field variable, D, denoted damage that measures the deteriorating effect of the voids. No consensus has yet been met as how to define D.

One way to define damage was introduced by Jansson and Stigh (1985). With Σ denoting the applied macroscopic stress, which is taken to be uniaxial tensile, and with $\dot{E}$ denoting the macroscopic axial strain rate, D is defined through

$$\dot{E} = B\left(\frac{\Sigma}{1-D}\right)^{n} \tag{1}$$

Here B and n are the material constants of power law creep. This is the strain rate equation of Rabotnov. It is the power law for secondary creep when $D = 0$. When D increases the strain rate increases too, which corresponds to tertiary creep. The macroscopic strain rate and stress are defined as the volume averages of the local strain rate $\dot{\epsilon}$ and stress σ. The base material is postulated to deform according to power law creep, i.e. locally

$$\dot{\epsilon}_{ij} = \frac{3}{2}B(\sigma_e)^{n-1}s_{ij} \tag{2}$$

where σ_e is the von Mises effective stress and s_{ij} is the stress deviator. This is the Odqvist three dimensional generalization of uniaxial power law creep, i.e. eq. (1) without D. The damage variable defined in this manner is independent of B and has been shown by Jansson and Stigh (1985) to be virtually independent of the creep exponent n. Thus, the tertiary part of the creep curve is solely attributed to damage. Continuum mechanical analyses of dilutely voided non-linear material, c.f. He and Hutchinson (1981) and Duva and Hutchinson (1983), gave the macroscopic strain rate for a given applied macroscopic stress state. Comparing these results with eq. (1) Jansson and Stigh (1985) gave the approximating values for D: $0.5Nd^3$ for penny shaped cracks and Nd^3 for spherical voids. Here N denotes the number of voids per unit volume and d their diameter. At higher void concentrations finite element calculations showed (Stigh 1986) that D is still independent of B and virtually independent of the creep exponent. The relation between D and the ultrasonic wave velocity was derived by Stigh (1987). Depending on the shape of the voids and on the direction of wave propagation, the velocity is given by

$$c/c_0 = 1 - \alpha D \tag{3}$$

where c and c_0 are the wave velocities of the damaged and virgin material respectively and a is a constant determined by the direction of propagation, the wave form and the shape of the voids. It is also dependent on the Poisson ratio for the base material. For a material with Poisson's ratio 1/3 one finds $a = 0.41$ for spherical voids and $a = 0.89$ for penny shaped cracks, the wave propagating normal to the crack face and the wave form being longitudinal. The results are based on assuming the wave length to be large compared with the structural size, e.g. thickness of void diameter and short compared with the structural size, e.g. thickness of the pipe wall. This is normally the case. The voids are smaller than or comparable to the grain size.

METALLURGICAL AND MECHANICAL OBSERVATION ON BURST PIPE

Figure 1 shows a pipe which has been part of a steam generator.

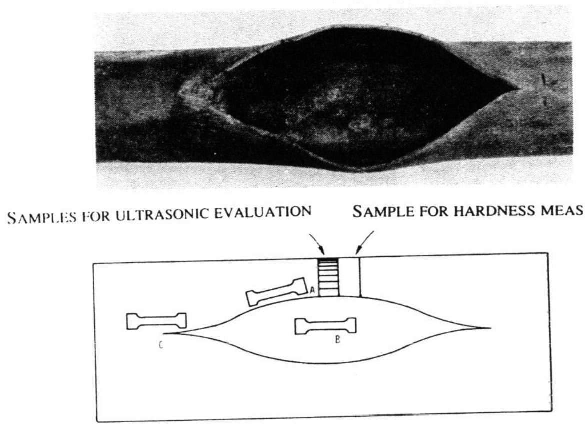

Fig. 1. Burst pipe from steam generator. Positions where samples were taken are indicated.

The pipe burst after about 155,000 hours of service at a nominal temperature of 236 °C and pressure of 28 bar. Its outer diameter is 76 mm and its thickness is 4 mm. This gives the nominal stress 13 MPa in the axial direction and 27 MPa in the circumferential direction. The material is normalized DIN 17175 with nominal chemical composition

	C	Si	Mn	P	S
percent	0.13	0.21	0.54	0.017	0.035

This is a ferritic steel with good characteristics at the nominal working conditions. However, in the burst pipe the carbon content was found to be 0.17 percent.

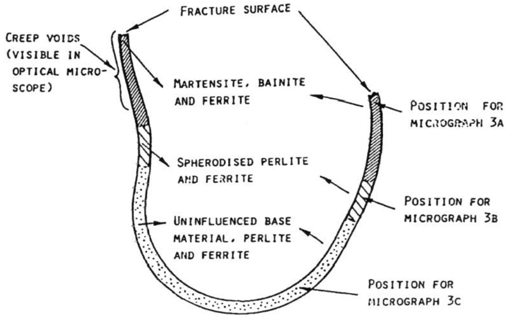

Fig. 2. Diametral section at the middle of the crack.

The crack is about 200 mm long and directed axially along the pipe. Microscopical evaluation of the structure in a diametral section of the pipe, cf. Fig. 2, reveals the presence of martensite with some ferrite close to the fracture surface, cf. Fig. 3a.

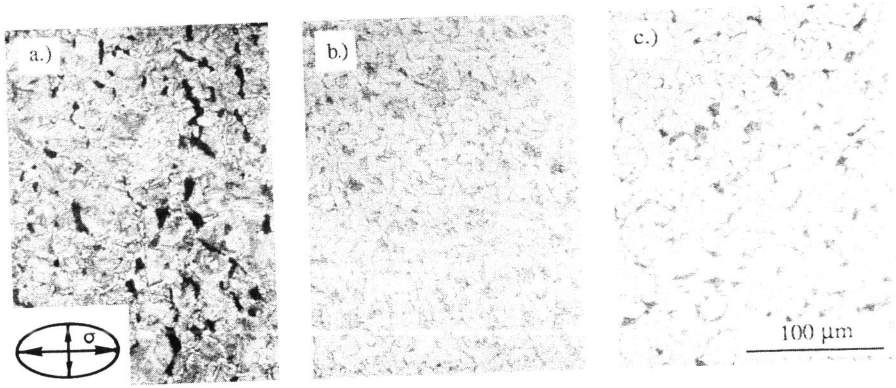

Fig. 3. Micrographs from positions along the circumference. a: Close to the fracture surface, note that microcracks are perpendicular to the maximum tensile stress. b: About 40 mm from the fracture surface. c: About 80 mm from the fracture surface.

About 35 mm from the fracture surface, in circumferential direction, the structure consists of martensite, bainite and ferrite. The next 15 mm consists of spheroidised perlite, cf. Fig. 3b. About 80 mm from the crack face the material consists of ferrite and perlite, i.e. the uninfluenced base material, cf. Fig. 3c.

This indicates that the temperature has been substantially higher on the side of the pipe where the crack has developed. The carbon content 0.17 percent and the presence of martensite shows that the temperature must have been 850-950 °C close to the fracture surface and diminishing in circumferential direction away from the fracture surface. Creep voids are also shown in Fig. 3a, these were developed before final fracture. At this very high temperature voids grow rapidly and fracture may occur within some days or even some hours. One possible cause for this high temperature is development of heat-insulating magnetite, which was found on the inside of the pipe. Probably the steam was also overheated due to bad flow in the pipe owing to local concentration of moisture.

The SEM picture in Fig. 4 was taken close to the crack tip at position C. It shows the presence of a wedge type creep void and the corroded fracture surface.

Three tensile tests were performed from samples taken at positions A, B and C, cf. Fig. 1. The stress strain curves are shown in Fig. 5. They show the hardening occurring at position A. Specimen C is somewhat more ductile and specimen B, the uninfluenced base material, is ductile. SEM pictures from the fracture surfaces after tensile testing are also shown in Fig. 5.

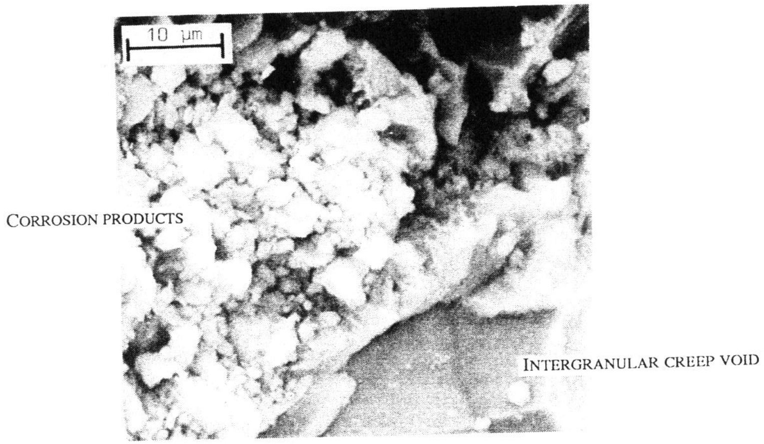

Fig. 4. SEM picture from the crack tip, showing corrosion products and an intergranular creep void.

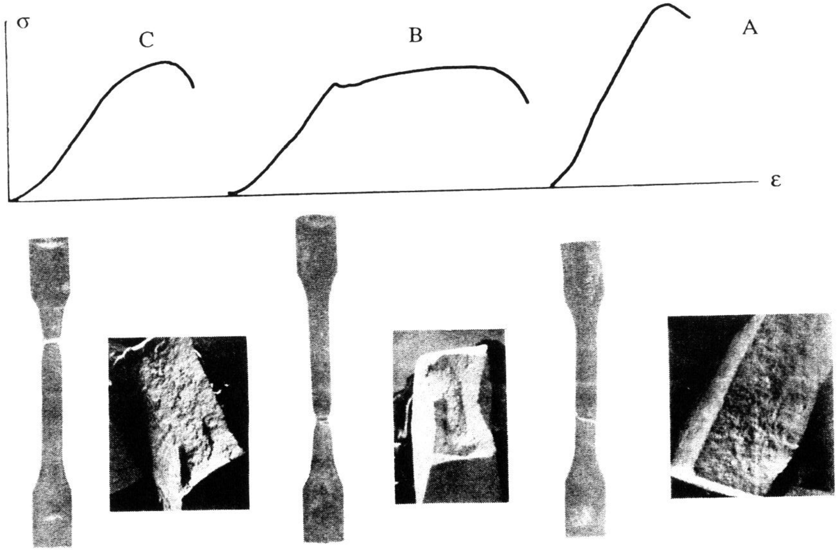

Fig. 5. Tensile tests of specimens cut out at positions indicated in Fig. 1.

Figure 6 shows a SEM picture from the intergranular dimpled fracture surface of specimen B.

Figure 7 shows results from micro hardness measurements. This also indicates the hardening that occurred.

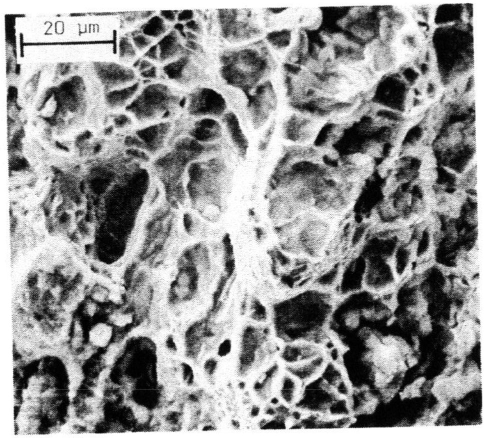

Figure 6: SEM picture from fracture surface of tensile test specimen B.

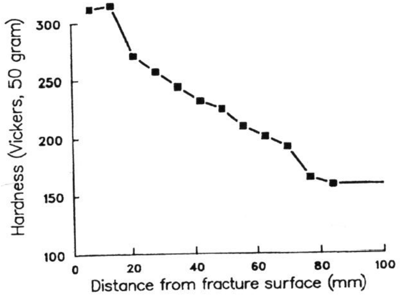

Figure 7: Results from hardness measurements.

ULTRASONIC VELOCITY

Twelve samples of the burst pipe were cut out at the positions indicated in Fig. 1, i.e. different circumferential locations. This was done in order to be able to measure the ultrasonic velocity with good accuracy in material with different levels of damage and different metallurgical structure. The samples were cut to about 10 mm length in the axial direction and 7 mm width in the circumferential direction. They were then ground to get parallel sides. The thickness of the samples varied from the nominal value 4 mm far from the fracture surface to 2.9 mm close to the fracture surface. The dimensions of each sample were measured with a micrometer screw and the longitudinal wave velocity was measured in all three directions. The ultrasonic device used was a Krautkrämer USIP 12 universal flaw detector together with a wall thickness module DTM 12 and a 10 MHz shock probe giving a wave length of about 0.6 mm. The multiple echo technique was used, i.e. the time difference between two consecutive echos was measured. Special care was taken to be sure that the same wave flank was used on the two echos. The accuracy is dependent on the length of the sample and was estimated to ±24 m/s in the radial, ±14 m/s in the circumferential, and ±10 m/s in the axial direction.

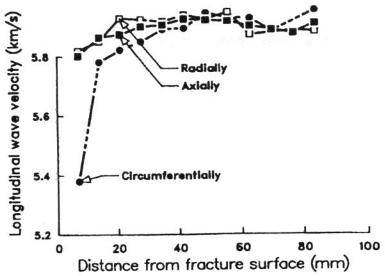

Fig. 8. Results from ultrasonic velocity measurements.

The results are shown in Fig. 8. It is shown that the ultrasonic velocity is about the same in the axial and radial directions but that the velocity in the circumferential direction is lower, compared to the axial and radial values close to the fracture surface starting about 30 mm from the fracture surface. This is interpreted as a result of creep damage in the form of grain boundary voids that was also observed in optical microscope in this area. The different values measured in the other directions are explained by the directionality of the void growth. The voids tend to grow on grain boundaries normal to the main tensile direction, i.e. the circumferential direction. Hence, it is expected that the wave velocity should be nearly unaffected in the axial and radial directions. The variation of the velocity in all three directions with distance from the fracture surface is attributed to differences in metallurgical structure.

Krautkrämer (1969) claims that variations in ultrasonic velocity due to different chemical compositions of steel are smaller than the variation that may occur due to different heat treatments. Hence, it is necessary to be able to distinguish between effects due to metallurgical structural changes and effects due to creep damage. A method to accomplish this, when testing pipe, is to measure the velocity in the axial and circumferential directions and compare the values. Damage is indicated if the velocity in the circumferential direction is smaller than that of the axial direction.

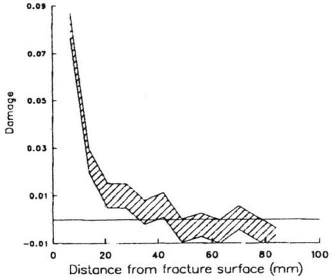

Fig. 9. Measured damage.

Figure 9 shows the variation of damage as calculated from the measured velocities and eq. (3). The error involved is indicated in the figure, only errors due to the velocity measurement being shown. The void shape is assumed to be crack like, i.e. $a = 0.89$ is used in eq. (3). The value c_o is taken to be the corresponding velocity in the axial direction which is more accurately measured than the radial velocity. The results indicate localization of damage to the area close to the fracture surface. This is a result of overheating in this area and perhaps also of some ovality. The strong stress dependence of damage growth would amplify such variations and localize damage to that area.

DISCUSSION AND CONCLUSION

The results show clearly the presence of creep damage in the form of creep cavities in the burst pipe. The metallurgical examination also revealed that the area around the crack had been exposed to extremely high temperatures, i.e. 850-950 °C. This is also indicated by the elevated hardness in this region and by the microscopical examination showing presence of martensite and grain coarsening.

The ultrasonic velocity was shown to be severely influenced by the presence of damage. In the circumferential direction the velocity had decreased about 10 percent near the fracture surface while the velocities in the radial and axial directions were almost unaffected. This is very similar to earlier experiments on copper, an austenitic stainless steel, and a Fe-Ni-Cr alloy casting. Changes in the ultrasonic velocity of this order of magnitude are easily detected. The strong difference between the effect of damage on ultrasonic velocity in the circumferential direction compared to the other two directions can be used to distinguish between damage and other metallurgical effects.

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