# DETECTION OF CREEP IN CR-MO STEEL BY MAGNETIC HYSTERESIS MEASUREMENTS

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## INTRODUCTION

Creep damage is the slow plastic flow of metal under stress and at high temperature, typically about 50% of the absolute melting temperature. The result is a very slow viscous flow of the metal which ends in sudden failure. This problem occurs in alloy steels that have been used in steam generators, turbines, and pipelines in power plants operating at high temperatures, typically in the range 500$^0$-600$^0$C, and under stress for an extended period of time. Creep failure occurs by a process of cumulative damage which involves plastic deformation, nucleation and growth of cavities at the grain boundaries, subsequent linkage of these cavities to form microcracks, and the propagation of these microcracks until failure.

While the creep process may be formulated in terms of detailed mechanisms [1] or continuum damage parameters [2], the predictive ability of available models are not yet of sufficient accuracy, even for simple loading conditions. Therefore prediction of material lifetime based on available models are not reliable. At present, the most widely used method to evaluate creep damage is the replication technique [3]. This technique employs a high resolution device such as a scanning electron microscope (SEM) to indirectly look at the material microstructure by inspecting a replica of a highly polished portion of the surface. Though the technique is sensitive to all stages of the microstructural changes, it requires a plant shutdown and substantial amount of time and effect to perform the replica examination. Also the replication technique can not detect subsurface damage.

It is well known that the magnetic properties of steels are highly sensitive to stress[4,5], strain [6] and inhomogeneities within the material, such as voids, cavities

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and microcracks. Néel [7] has shown that when a domain wall intersects a spherical void for example, there is a reduction in magnetostatic energy of $\Delta E = \pi\mu_0 M_s^2 r^3/9$, where $M_s$ is the saturation magnetization of the material and r is the radius of the void. Since creep leads to the nucleation of voids and cavities, techniques which measure the local magnetic properties of steels should be useful for the detection of creep damage [8]. Recently Chen et al. [9] found that structure sensitive parameters such as coercivity and remanence decrease with creep damage and this could be due to the effects of (1) reduction of domain wall pinning by moving defects to grain boundaries and (2) creation of local demagnetization field due to grain boundary cavitation. As a result a numerical calculation, based on these effects and a modified model of hysteresis [4], was performed, which simulated the trends in experimental data.

This paper is concerned with the magnetic hysteresis measurement of creep damaged Cr-Mo steel pipe and the investigation of the correlation between creep damage and magnetic properties. The microstructure of the pipe sample has also been studied to find the metallurgical changes occurring during creep damage of the material.

## MATERIALS AND EXPERIMENTAL PROCEDURE

The materials for this experiment were service-aged 2.25 Cr - 1.0 Mo pipe steel from General Atomics cut from a steam header with an inside diameter of 12.1 cm and outside radius of 21.6 cm. The test samples were prepared by cutting seven flat specimens with thickness of 3/10" from different layers of the pipe steel, so that the inner side surfaces of the sections represented respectively planes at 3.30 cm, 4.32 cm, 5.33 cm, 6.35 cm, 7.37 cm, 8.38 cm and 9.40 cm from the outside surface of the pipe. ( Labelled as layers 0, 1, 2, 3, 4, 5, 6, 7 respectively, see Fig.1).

Magnetic measurements were performed on the surface of each specimen that was closer to the inside of the pipe. Measurement was made using the Magnescope [10], which is a computer controlled magnetic inspection system together with an inspection head which can detect the magnetic field on the surface of the specimen and the

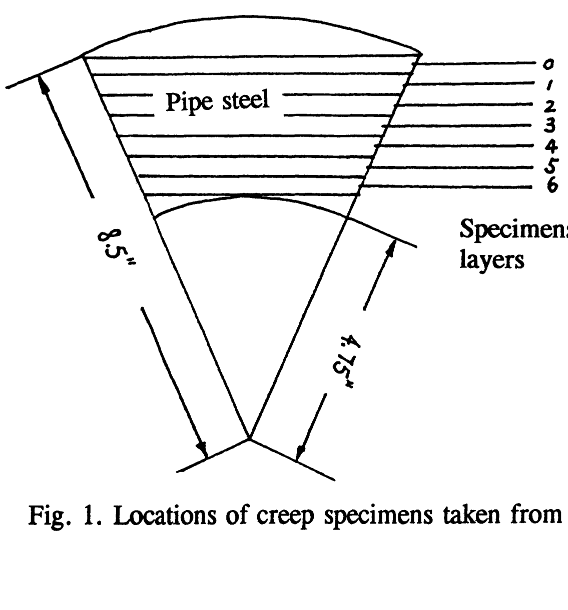


Fig. 1. Locations of creep specimens taken from steam header.

magnetic flux through the core of the inspection head with minimal material preparation. Hysteresis parameters, such as coercivity, remanence and hysteresis loss, were extracted from each measurement. A small piece was cut from each sample and analyzed using optical microscopy after mechanical polishing and chemical etching.

## RESULTS

Magnetic measurements were performed with the inspection head oriented at 5 different angles ( $0^0$, $22.5^0$, $45^0$, $67.5^0$ and $90^0$) with respect to the long axis of the pipe. In each case, six hysteresis loops were taken at different locations of each sample. Except for the $0^0$ case, all the experimental results were quite similar, showing a general decrease in coercivity $H_c$ and hysteresis loss $W_h$ from the outside layer to the inside layer while remanence $B_r$ and maximum flux density $B_{max}$ showed little evidence of change. Typical test results of magnetic properties at different layers are shown in Fig. 2 for the $90^0$ orientation. In this figure, $H_c$ shows an approximately 12% reduction from outside to inside and $W_h$ shows about a 6% reduction while $B_r$ and $B_{max}$ remain essentially constant.

Optical micrographs showed that there was little difference in microstructure between different layers of the pipe in terms of grain size. Also, no significant grain boundary cavitation was observed in these samples. Micrographs of the surface are shown in Fig. 3.

## DISCUSSION

During the creep process, impurities and dislocations segregate out of the grains and accumulate on grain boundaries. As this process continues, two effects on microstructure are introduced: 1) The impurity (or general defect) density inside materials is decreased as impurities and other defects such as dislocations accumulate on grain boundaries, 2) grain boundary cavities are nucleated and developed. It is known that when a domain wall interacts with an impurity (or other kind of defect), the magnetostatic energy of the wall is reduced, and therefore, the impurity impedes the domain wall motion. As the defect density decreases during the creep process, the domain wall experiences less pinning and hence a lower coercivity of the material is expected [9]. Also, as grain boundary cavities nucleate and develop, local demagnetization fields form in the vicinity of the cavities [9]. Therefore, as creep damage continues, the remanence is expected to decrease.

Of the two external primary factors (stress and temperature) which determine creep damage, stress is the major factor accounting for the different degree of creep damage for specimens from the different layers of the pipe wall under this investigation. The operating temperature of the pipe was essentially uniform across the diameter, varying by perhaps one or two degrees, as the pipe was operated under heavy insulation. However, the stress inside the pipe was not uniform. When in service, the pressure inside the pipe was much higher than that of the outside, and therefore, the stress experienced by the inside layer was higher than that of outside layer. Since creep damage increases with applied stress at a fixed temperature, a general decrease in coercivity from outside to inside pipe wall was expected, and this agrees with magnetic measurements.

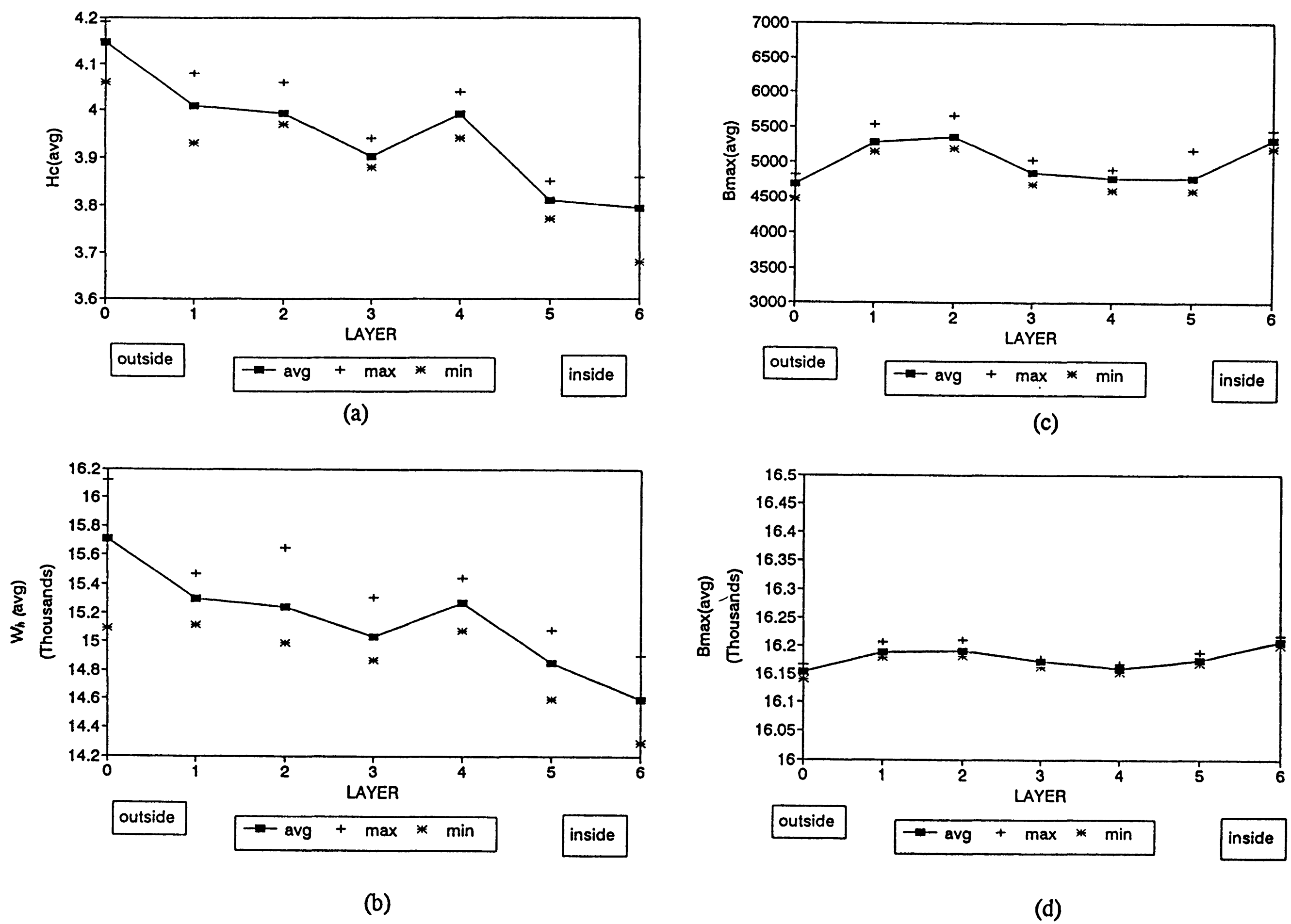


Fig. 2. Magnetic properties of pipe steel at different layers. (a) Coercivity, (b) Hysteresis loss, (c) Remanence, (d) Maximum magnetic induction. (All are relative value.)

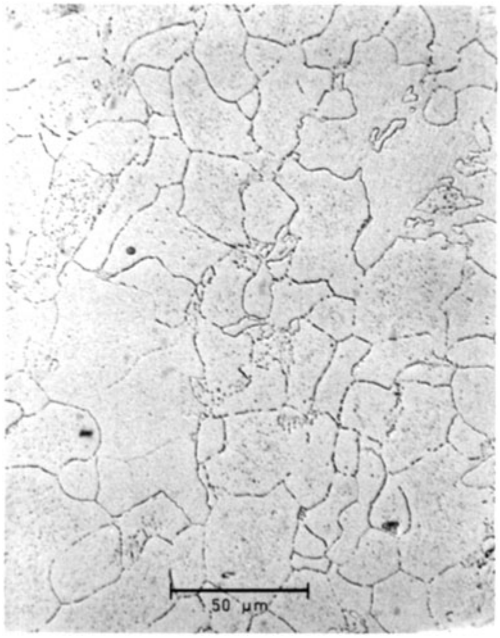

Fig. 3a.

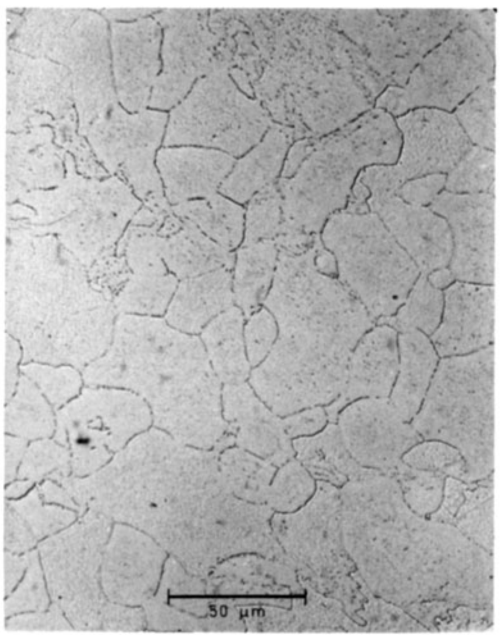

Fig. 3b.

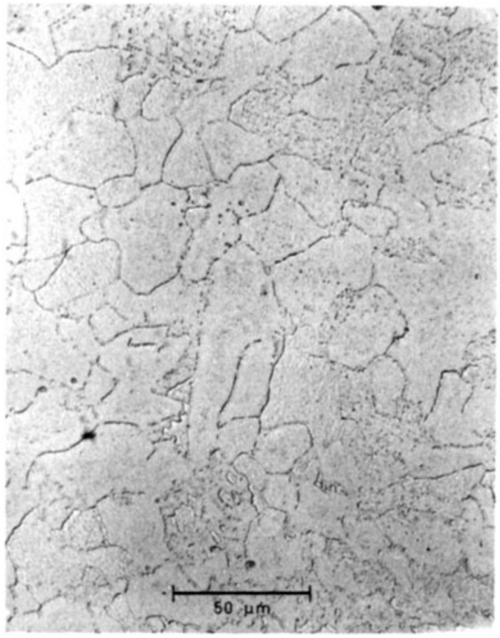


Fig. 3c.

Fig. 3. Microstructure of pipe steel at different locations (a) inside layer, (b) middle layer, (c) outside layer.

Using the fact that remanence and maximum flux density remained constant from inside to outside, one might conclude that this material was in an early stage of creep damage, when cavitation at the grain boundaries was only at its nucleation stage, and no significant local demagnetization effects were present. Metallurgical examination corroborates this explanation since no detectable amounts of cavitation were seen on optical micrographs and the microstructure seems to be uniform from outside to inside.

Although the decrease in coercivity could be caused by increasing residual tension remaining inside the pipe wall after being taken from the service, the expected corresponding remanence increase with tension did not occur. Therefore residual stress could not be the cause of the decrease in coercivity. Our conclusion is that the behavior seen in the coercivity could be a signature of early creep damage, in which the first changes are a decrease of pinning site density in the grains, as defects begin to migrate to the grain boundaries and later coalesce to form cavities.

## CONCLUSION

Magnetic hysteresis measurements have been investigated as an NDE method for detection of creep damage in Cr-Mo steel. Test results showed that coercivity and hysteresis loss can be used to characterize creep damage, even in the early stage of the creep process. The general decrease in coercivity with creep damage is in agreement with the previous experimental results and also with theoretical hysteresis modelling studies [9].

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