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MECHANISM OF DIFFUSION-CONTROLLED BRITTLE FRACTURE

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ABSTRACT

Two generations of UHV testing systems were developed, one for testing pre-cracked specimens at constant displacement and the other at constant load, and they were supplemented by a computer-controlled potential-drop system for measurement of crack-growth rates. The latter system was also developed during this project. Experiments were carried out on the alloy Cu-8%Sn which was used as a model system for the phenomenon of diffusion-controlled fracture by intergranular decohesion resulting from the ingress of an embrittling element from a free surface as the result of an applied stress. The cracking phenomenon found earlier in alloy steels, and shown to be due to surface-adsorbed sulfur, was reproduced in the Cu-Sn alloy. This provided verification of the earlier proposed mechanism for the cracking phenomenon in the alloy steels, known as stress-relief cracking, and it also provided support for the hypothesis that the phenomenon was of a generic nature.

In conjunction with the experimental work, the development of a quantitative theory of this class of brittle fracture, which we have termed "dynamic embrittlement", was begun. The first report of this theory has been completed, and it is consistent with the case of embrittlement by a fast-diffusing, strongly embrittling element in a creep-resistant material, as in the case of sulfur in steels. The work of expansion of this theory to the general case of dynamic embrittlement of any alloy system from any external source of impurity element is still proceeding.

INTRODUCTION

This research dealt with a class of brittle fracture of metallic materials which, although rather widespread, has received relatively little attention and which, in fact, is commonly viewed in terms of isolated phenomena, rather than as a generic class. The unifying elements of this class of fracture are that the separation process results from decohesion, almost always along interfaces, induced by the intrusion of some impurity (or sometimes a solute element), and that crack growth is quasi-static when measured on the scale of tens of micrometers. The decohesion process is accompanied by plasticity, at least on the scale of the dimensions of the crack tip, because the materials are deformable. Some of the material separation may occur by plastic tearing, but this is a result of the

presence of the brittle cracking, which elevates local stresses. (The evidence of plasticity often confuses the evaluation of the fracture process.)

It needs to be emphasized that the interfacial weakening occurs *as a result of* the application of a tensile stress across the interface at a temperature where interfacial diffusion can occur. That is, the foreign element enters the interface from the free surface in response to the application of stress. Thus, whereas the free surface has a high concentration of the impurity, the initial condition of the interface is often effectively free of impurity segregation, and a rapid application of stress would not produce the embrittlement. This is to distinguish the phenomenon from the well-known examples of impurity-induced interfacial embrittlement, such as temper embrittlement of steels, which manifest themselves at high stresses at ambient temperatures.

Within this class of fracture we find most cases of embrittlement by liquid metals and low-melting-point solid metals, many cases of interfacial cracking due to particular gaseous environments, including hydrogen, and cracking which results from the intrusion of a surface-segregated element which originates from within the alloy. (The latter would include elements which do not segregate to a significant degree to internal grain boundaries; they are only surface active with respect to the free surface.) From this class of fracture are excluded such time-dependant crack-growth phenomena as diffusive transport of atoms along grain boundaries away from a crack tip (i.e., creep crack growth), forms of stress-corrosion cracking which occur by anodic dissolution of material at a crack-tip, and cracking by cyclic plasticity, as in fatigue.

The research was originally motivated by a study of the brittle form of stress-relief cracking of low-alloy steels. This is found in the heat-affected zones of weldments, where the steel has been heated to temperatures above 1200°C and cooled fairly rapidly (e.g., by heat loss to the surrounding colder metal). The cracking occurs when the weldments are subsequently given a stress-relief heat treatment in the 500-to-600°C range to allow the residual stresses due to welding to be relaxed by creep.

The decohesion mode of stress-relief cracking can predominate within certain ranges of temperature and applied stress; when it does, the fracture surface is remarkably brittle in appearance. However, it is more usual to find it accompanied by the other forms of high-temperature fracture, involving cavitation around inclusions, usually sulfides, and plastic tearing between cavities or between areas of decohesion. In some temperature-stress regimes the decohesion mode can be absent completely; the temperature must be high enough to permit the requisite diffusion, but not so high as to prevent the attainment of a high stress. The stress must be high enough to drive the diffusion and to cause the decohesion, but not so high as to produce large-scale plastic flow.

PROGRESS

The goal of this research program was to extend the study of time-dependent decohesion to other materials and to other sources of embrittling elements. The first system to be studied was Cu-8wt% Sn, the base of a commercial bronze, which was known to suffer brittle intergranular cracking at elevated temperatures. Tin is an embrittling element in steels, and it is known to segregate to free surfaces in Cu-Sn alloys; therefore, it was chosen as a possible analog of the stress-relief cracking phenomenon.

Our major initial tasks in carrying out this research were twofold: It was necessary, first, to develop a testing procedure for measuring crack-growth rates in materials loaded in ultra-high vacuum at elevated temperatures, and, secondly, to develop an approach to the micro-mechanical modeling of the processes which can occur at a crack tip in the presence of a mobile embrittling species, so that useful measurements of growth rate can be made and properly interpreted.

The development of the system for measurement of crack-growth rates was initially carried out using loading at a constant displacement, during which the actual load would decrease as the compliance of the specimen increased with crack length. This was the method used in previous studies. However, instead of the notched-bend type of specimen used previously, it was decided to employ the compact-tension specimen more commonly used in fracture-mechanics studies. Because of the wealth of knowledge which already existed on the behavior of the MnNiCrMo steel used earlier, this material was selected for the test development. After an extensive period in which great difficulties in achieving dimensional stability in the loading train, the constant-displacement approach was abandoned in favor of a constant-load approach. The overriding advantage of the latter was that variations in temperature along the loading train had no effect on the tests.

The crack-growth in the Cu-Sn alloy was studied on side-grooved compact-tension specimens in the temperature range 250 to 325°C in a vacuum in the range 1 to 4×10^{-8} Torr. Prior to the test, the specimen was cleaned in the test chamber by heating to 400°C in one atmosphere of hydrogen; the efficacy of this cleaning was checked by Auger electron spectroscopy on specimens similarly treated in a separate UHV system. The crack growth was monitored by means of a microcomputer-controlled reversing DC potential-drop method. The configuration of current and voltage leads was the one optimized in a finite-element study by Aronson and Ritchie. During the tests the ratio of the electrical resistance of the cracking specimen with respect to a reference resistance was recorded as a function of time. The crack length corresponding to each resistance ratio was obtained from a calibration curve of resistance ratio vs crack length. The results of the experiments on precracked specimens are reported in detail in the preprint included as Appendix A. The

results can be summarized as follows: The behavior of the Cu-Sn alloy at 250 to 325°C was found to be exactly analogous to that of the steel at 500 to 650°C. That is, the same quasi-static intergranular decohesion was shown to occur, and the same kind of intermittent crack propagation was found in both materials. The conclusions are two-fold: First, the earlier explanation for the sulfur-induced cracking of steel is verified. Second, the phenomenon is shown to be of a generic nature and to constitute a new class of brittle fracture.

A second kind of fracture experiment was also carried out. This involved the use of circumferentially notched tensile specimens pulled in vacuum in the above temperature range at very slow cross-head speeds. The main value of these experiments is that the intermittent nature of the cracking phenomenon was made dramatically clear by the occurrence of load drops on the load vs time curves. The details of these results are contained in the preprint included as Appendix B.

Finally, the first stage of the development of a theory for this phenomenon of dynamic embrittlement has been completed. It applies to the case in which (1) the surface concentration and diffusivity are so high that the concentration of the impurity on the surface at the crack tip can be assumed to remain constant, (2) the impurity is a strong embrittling element, so that crack nucleation occurs in a short time, and (3) the material is highly creep resistant, so that the crack-tip stress field can be taken as constant for short times. This case is consistent with sulfur-induced cracking in steels, but not with Sn-induced cracking of the Cu-Sn alloy. Restriction number 2 allowed us to use only the stress-driven part of the impurity ingress, ignoring the effect of the resulting concentration gradient on diffusive mixing. The results are given in the preprint included as Appendix C, and they show that a kind of wave front of increasing concentration of impurity is driven into the grain boundary at the crack tip, toward the point of the maximum in the elastic-plastic stress field. This would produce a front of decreasing cohesive strength which would allow decohesion when the curves of falling cohesive strength and rising local stress cross. The calculated crack growth kinetics are completely consistent with the measured cracking rates found in the alloy steel embrittled by surface-adsorbed sulfur.

This theory can be applied to any decohesion-type of fracture resulting from an element concentrated on the free surface, including liquid- and solid-metal embrittlement, embrittlement from a gaseous species, including hydrogen, and embrittlement from an element which segregates to free surfaces from solid solution, as in the steel and the Cu-Sn alloy. This is a new generic class of fracture, which has distinct and well-defined characteristics, and this work, therefore, has opened up a new field of inquiry which has relevance to many important failure phenomena.

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