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Anne J. Sunwoo

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Lawrence Livermore National Laboratory

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Anne J. Sunwoo

University of California
Lawrence Livermore National Laboratory
Livermore, CA 94550

Introduction

Ultrahigh-strength H13 steel is a recommended die material for aluminum (Al) die casting [1]. The steel is hot-worked and air-hardened to produce a martensitic microstructure, which in turn provides good resistance to softening and to thermal fatigue. Chromium and vanadium are added to the steel to increase resistance to high temperature oxidation, corrosion, and erosive wear. Other beneficial characteristics of the steel include ease of forming, good weldability, relatively low coefficient of thermal expansion and acceptable thermal conductivity. These attributes are important in die materials because the performance of dies is directed related to being able to withstand the erosive action of molten Al under high injection velocity, and to thermal gradients within the dies and frequency of exposure to high temperature. Because the steel is well-adapt to these conditions, dies made from H13 steel can be safely water-cooled during hot working operations without cracking.

However, after time in service the qualities reported for this material were not maintained. Instead, the dies exhibited severe surface cracking and excessive wear. Figure 1 shows a section of a die where the service life was shortened due to extensive surface cracking. In addition to surface cracking problems, there is also a problem with erosive wear in the die caused by the high pressure injection of molten Al. These problems lead to expensive repair and replacement costs. Hence, an exploratory study was initiated to investigate the causes for surface cracking of H13 dies.

Experimental Procedure

Microstructural characterization was performed on small sections of the as-received die. The samples were polished in the through-thickness direction using a standard polishing technique. Both optical and scanning electron microscopy (SEM) were employed to characterize the polished and fracture surfaces. Rockwell C Hardness (HRC) measurements were taken from the outer and inner surfaces of the die.

A quench study was performed to qualitatively simulate the thermal cycle. The sample was heated to 1200°F (676.7°C) (the temperature at which a molten Al is used in the plant), for one minute and water quenched. Thermal cycling was repeated for 35 times, while monitoring the polished surface every fifth cycle for any surface changes.

Results and Discussion

The composition of H13 steel in wt-% is 0.4C-0.5Mn-1.0Si-5.0Cr-1.5Mo-1.0V- bal. Fe. The sulfur content in H13 is limited to no more than 0.04 wt-%, which is an innocuous amount if the sulfides are homogeneously distributed in the steel as spheroidized particles. However, because the H13 steel has been heavily hot worked, the resulting morphology of sulfides is stringers aligned in the rolling direction. Since there is high surface energy associated with these high aspect ratio stringers, they provide a preferential crack path into the die. Figure 2 shows a cross-sectional view of a crack following the stringer and its fracture surface. Cracks can also propagate along the weakest interface in both an intergranular as well as a transgranular mode (Figure 3). Moreover, the resistance to fracture of the steel is greatly compromised due to the presence of the stringers. In Figure 4a, the fracture surface reveals a uniform distribution of the stringers, and because the cracks initiate externally, the crack surfaces become heavily oxidized, displaying a distinct interface (Figures 3b and 4b).

Although the internally present sulfide stringers provide easy access into the interior of the die, the driving force for crack propagation is externally induced transient thermal gradient within the die which is created by the water quenching (compression)-molten Al injection (tension) process. As the thermal-fatigue continues, the stress intensity at the crack tip will increase, causing the crack to propagate. The effect of repeated thermal cyclic strain on the die is shown in Figure 5. The figures also reveal that corrosion plays an active role in crack initiation, starting with surface pitting. The quench test showed that after about 20 cycles, pitting occurred.

The amount of corrosion along the surface of the cracks is inversely proportional to the depth of crack.

Loss of thermal-fatigue resistance may have been enhanced by decarburization of the die surface. The removal of carbon from the surface leads to loss of strength and the decarburized material becomes less resistant to thermal-fatigue. Figure 6 shows a partially decarburized surface layer from the as-received die sample. The suggested hardness range for H13 die material used for Al die casting is between 44-48 HRC, which is equivalent to about 230 ksi tensile strength [2]. The hardness measurements showed that the overall hardness of this die was lower than the suggested hardness and that the exposed surface had slightly lower hardness of about 41 HRC than the unexposed surface hardness of about 42 HRC, which is a minimum of 20 ksi lower in strength. Thus, the decarburized surface from high temperature exposure in a unprotected atmosphere may have some effect on the difference in the hardness. In the die casting environment, the die surfaces will continue to decarburize, losing their desirable surface properties.

Recommendations

The results of this exploratory investigation suggest that surface cracking is caused by interrelated factors, internal to the die material as well as externally induced conditions. If the results are confirmed, then changing the morphology of sulfides from stringer to spheroidized particles may eliminate a preferential crack path into the die and improve resistance to surface cracking [3]. The morphology of the sulfide inclusions can be controlled by the cooling rate [4], the extent of hot reduction [5], and the post-deformation heat treatment [6].

Externally, decreasing the thermal gradient, i.e. lessening the effects of thermal-fatigue, will reduce the stress intensity at the crack tip, which hinders crack propagation. Moreover, protecting the die surface will prevent decarburization and thereby minimizes the loss of surface strength and of resistance to thermal-fatigue, corrosion, and oxidation. For example, nitriding the die will provide a protective layer as well as a highly wear resistant surface [1].

Acknowledgments

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Figure Captions

Figure 1. Section of H13 steel die: a) low magnification; b) higher magnification showing erosion around the hole. The service life was shortened due to severe surface cracking problems.

Figure 2. SEM micrographs: a) a cross-sectional view of a crack following the sulfide stringer; b) corresponding fracture surface showing crack path into the die through sulfide (dark region).

Figure 3. Optical micrographs showing crack propagation into the die by following the weakest interface: a) between the stringers and the matrix; b) in an intergranular and a transgranular mode.

Figure 4. SEM fractographs: a) a low magnification view of fracture surface showing a uniform distribution of sulfide stringers; b) the oxidized surface represents previously cracked surface.

Figure 5. Optical micrographs: a) a surface view showing the effect of repeated thermal cyclic strain on the die; b) a cross-sectional view showing the effect of corrosion enhanced crack opening.

Figure 6. Optical micrograph showing a partially decarburized surface layer from the as-received die sample.

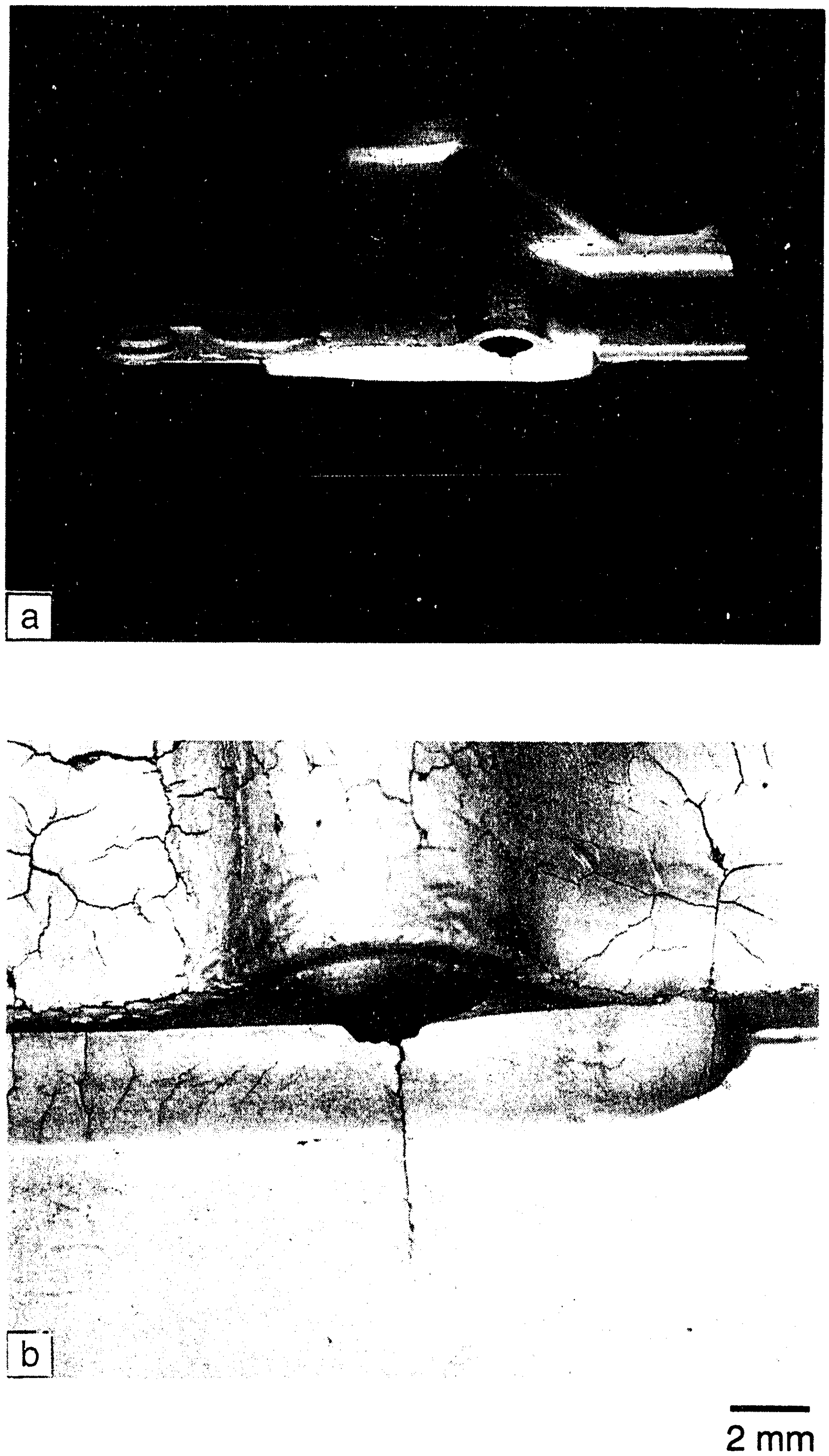

Figure 1

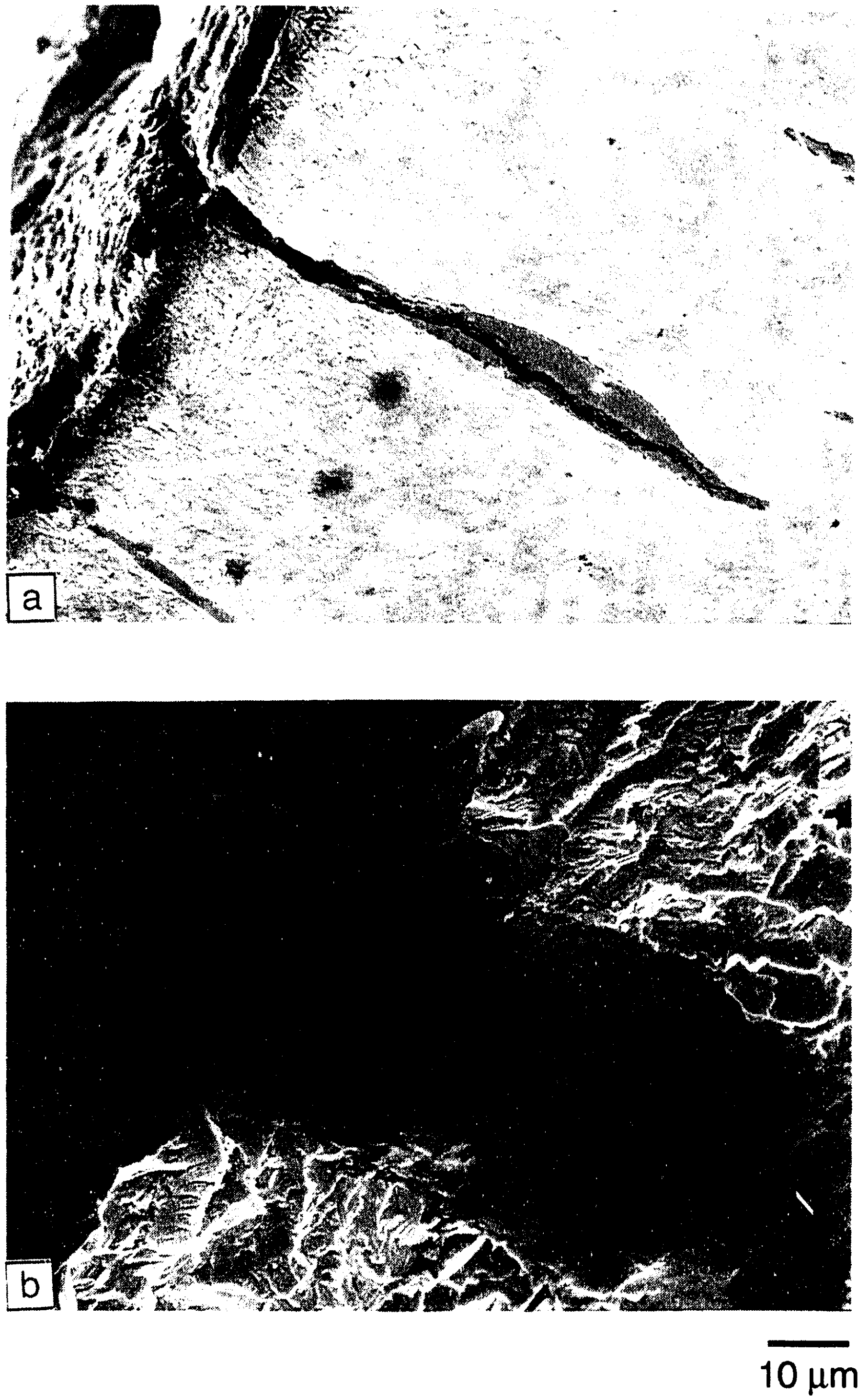

Figure 2

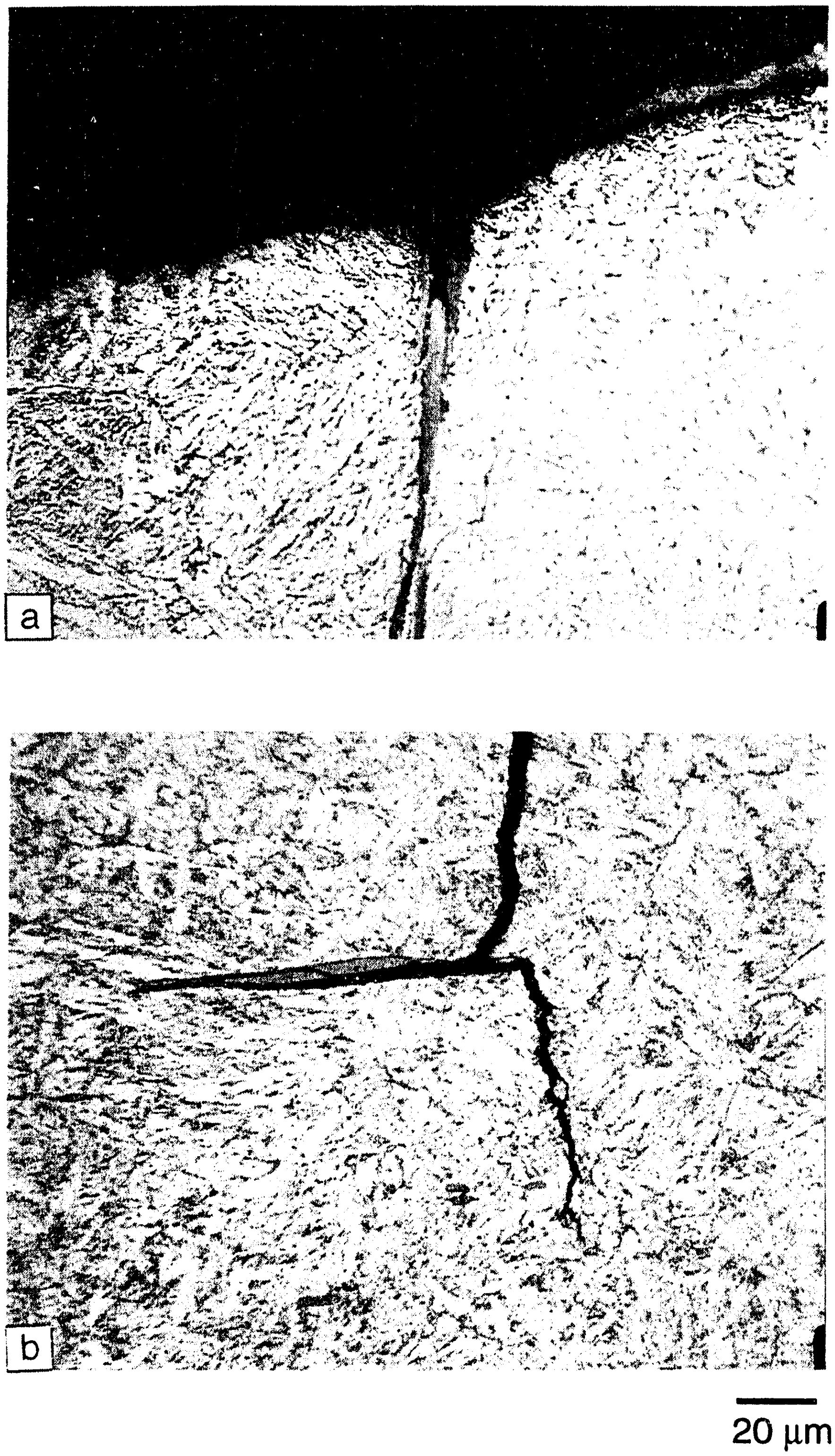

Figure 3

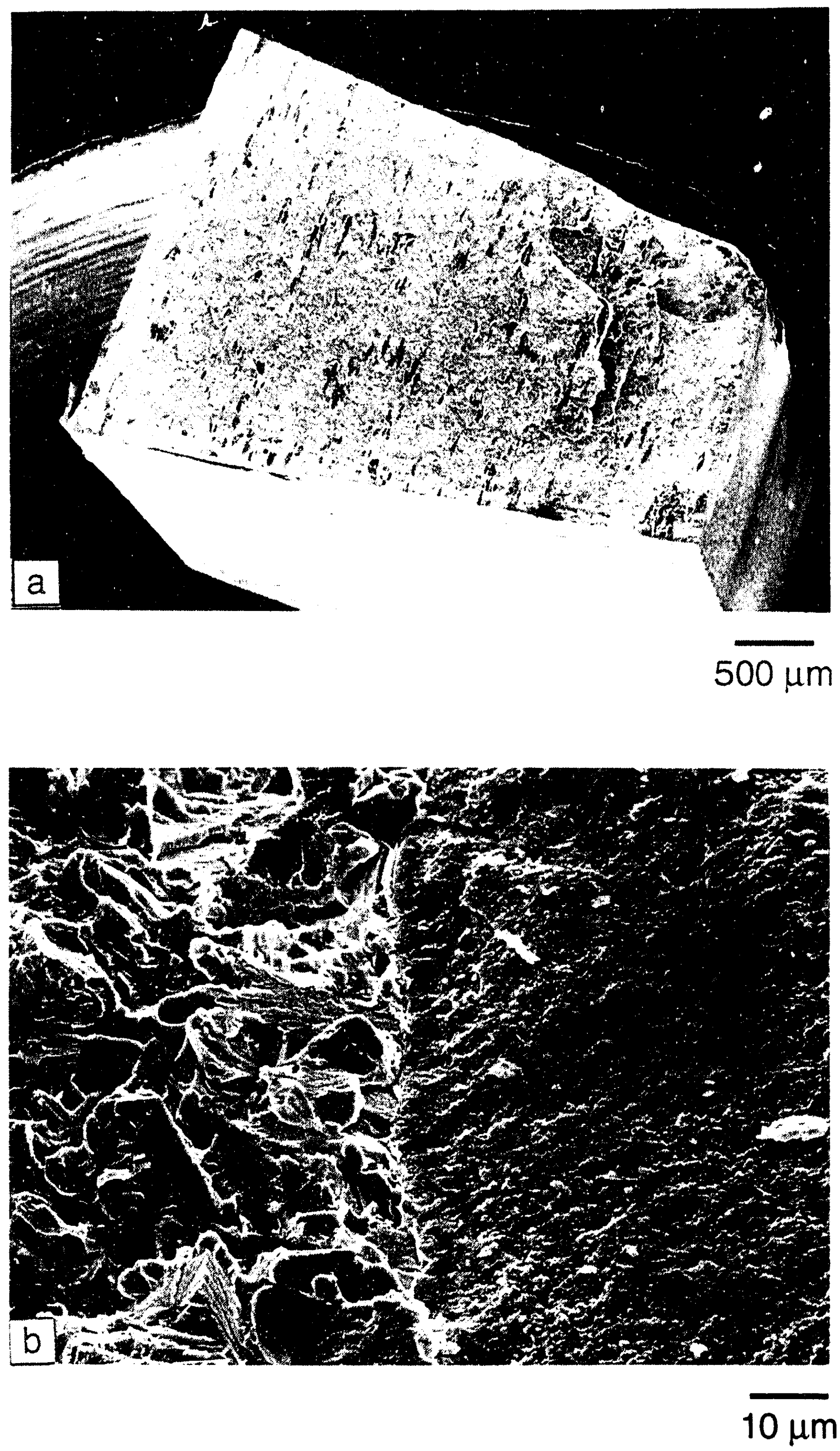

Figure 4

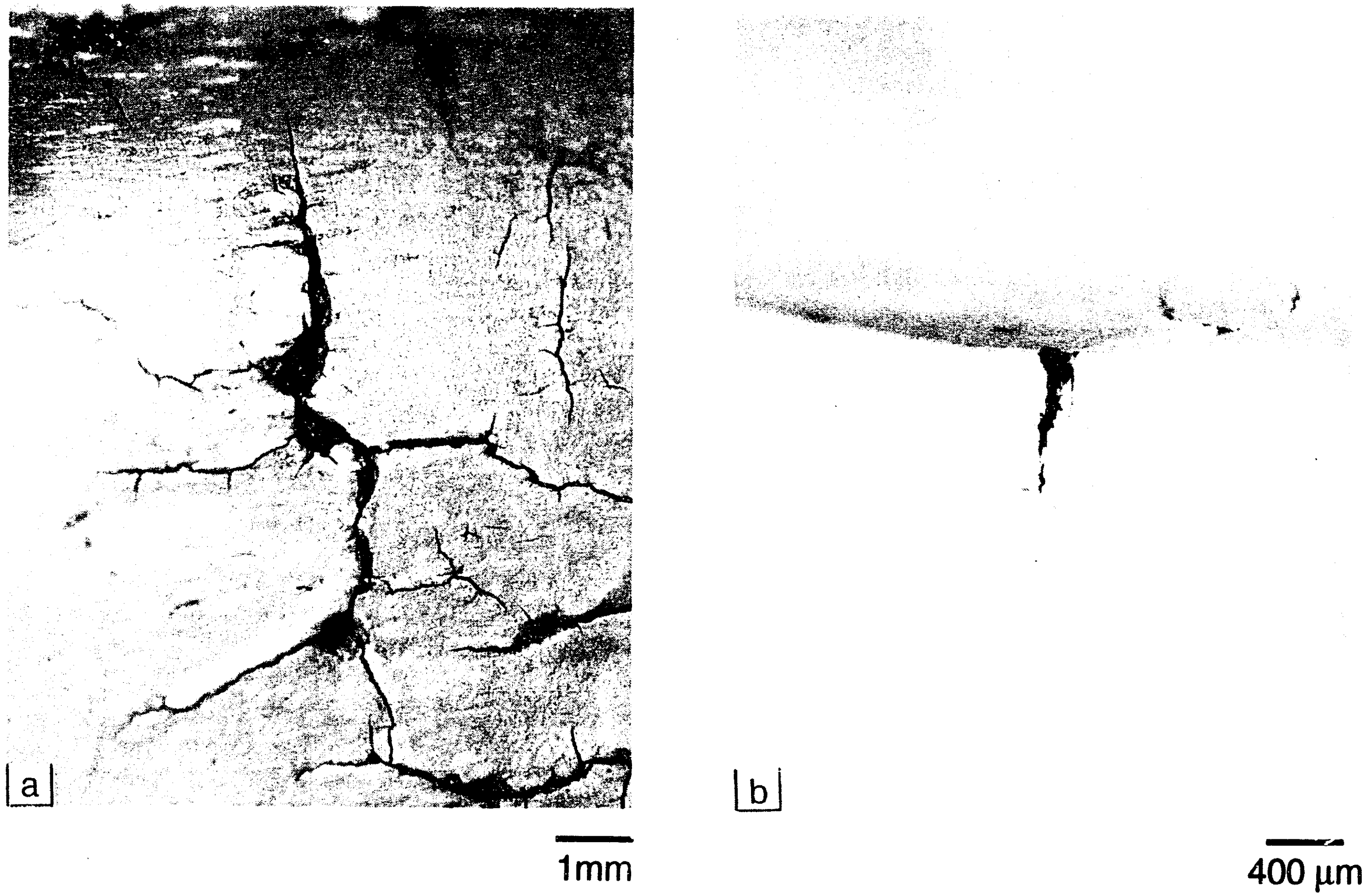

Figure 5

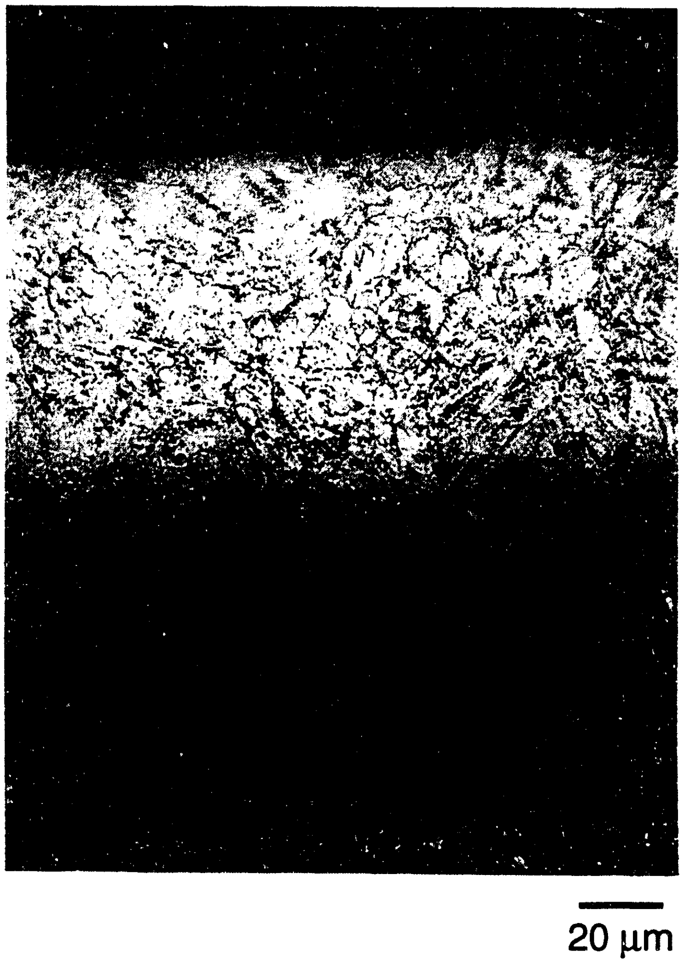

Figure 6

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