THE FRACTURE OF WROUGHT METALS

FINAL REPORT

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The mechanism of prestrain embrittlement in wrought metals was examined in three alloy systems: Armco iron, 7075-T651 aluminum, and a copper-SiO_2 alloy. Specimens were compressively prestrained, then tested in tension in and transverse to the direction of compression. Prestrain embrittlement was observed in all three alloys, depending on test conditions. In the copper-base alloy, which was in the form of thin sheet, the retained tensile ductility was reduced linearly by in-plane compressive prestrain. Fracture was initiated by crystallographically-oriented voids generated at particle-matrix interfaces during compression. The

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20. Abstract (Continued)

behavior of Armco iron was similar in that particle-matrix void nucleation during compression provides fracture initiation sites that lead to brittle cleavage failure at room temperature during subsequent notch tensile testing. Prestrain had little influence on smooth bar tensile test results. Crystallographic texture development was shown to play a part in the embrittlement but tests under high pressure that suppressed void nucleation showed the role of texture to be secondary. Prestrain embrittlement in the aluminum alloy results from the interaction of intense shear bands, formed by sufficient compressive prestrain, with the grain boundaries to give a partially intergranular fracture.

FOREWARD

The bulk of the metallic materials used in the nation are in the wrought form and it is well known that in the majority of these materials there is an anisotropy of properties that is a result of their processing history. The magnitude of their anisotropy is a function of the basic alloy composition and structure, cleanliness and the processing details. This gives rise to fibering or ease of "lamellar tearing" in plate and generally poor through-thickness or transverse properties in rolled or drawn material. Super imposed on this anisotropy in properties of wrought materials is an additional problem with the ductility of wrought materials that is well identified and less understood. This is an anisotropic loss in ductility in cold or warm deformed materials that has been termed, among others, "prestrain embrittlement". The phenomenological aspects of the problem have been studied in the past in a number of materials by stretching previously compressed materials and by bending and unbending rods. The most extensive work was carried out by Mylonas et al. on ship plate (1-5).

PROBLEM UNDERTAKEN

This current investigation was undertaken to determine the mechanisms responsible for this prestrain embrittlement and to determine the reasons for its anisotropy. Three different alloy systems were studied to determine how widespread this form of embrittlement was and whether the mechanism of prestrain embrittlement was the same in all alloy systems: iron-and silicon-free 7075-T651 aluminum, copper - 0.1 wt. percent silicon, and Armco ingot iron. These metals were prestrained various amounts in uniaxial compression followed by testing in tension to failure both in the compression direction and transverse to it. The retained tensile ductility was determined, the nature and morphology of the fracture was established and changes in the microstructure with deformation were examined in detail.

SUMMARY OF RESULTS

The results of this investigation have established that prestrain embrittlement is a not uncommon phenomenon, occurring in the three alloy systems studied. The mechanistic details were found to be different in each alloy, however. Nevertheless, in each case fracture initiation was strongly tied to particle-matrix interaction.

The copper-silicon alloy was in the form of thin sheet. It was upset in the plane of the sheet using a specially designed fixture. The alloy was studied in two different conditions: as a dilute copper-silicon solid solution and as oxidized to form a low alloy copper containing spherical SiO_2 particles. The high purity solid solution was unaffected by prestrain in terms of reduction in area at fracture. In every case, the R.A. approached 100 percent. The oxidized alloy failed by void growth and coalescence. Voids were particle nucleated; the ductility was reduced linearly by increasing compressive prestrain. Moreover, the properties were the same in the direction of compressive prestrain and transverse to it.

The iron-and silicon-free aluminum alloy 7075-T651 was supplied by the Frankford Arsenal in the form of 2 in. plate permitting anisotropy to be studied. A distinct prestrain embrittlement was observed at a strain of 0.25 to 0.3, particularly when tested in the short transverse direction after prestraining in the short transverse direction. At the other extreme, the alloy was least affected when both precompression and testing were in the longitudinal (rolling) direction of the plate. The embrittlement was brought on by the rapid increase in intensity of shear banding in the alloy with increasing prestrain. Electron microscope studies showed these regions to be zones of high dislocation density but free of the coherent precipitate particles that strengthen the matrix. Apparently dislocation channeling in the bands caused reversion of the strengthening particles, leaving the bands weak. These then act as fracture nuclei under subsequent tensile loading. Impingement of the shear bands on the grain boundaries results in grain boundary failure. The lath-like morphology of the grains in the rolled plate gives rise to the observed directionality in prestrain embrittlement in this alloy. Although this alloy was essentially free of iron and silicon intermetallic inclusions, it contained chromium for grain control. Thus, the grain boundaries were generously populated with what is believed to be E-phase $Al_{18}Cr_2Mg_3$ intermetallic particles roughly 100 nm (1000Å) in size. These particles led to the relative grain boundary brittleness in this alloy.

The Armco iron studied was in the form of rod; therefore, all compressive prestraining was axial although tensile tests were carried out in the precompression direction and also in the transverse direction. There was no observed prestrain embrittlement in either direction when tension testing was carried out with smooth tensile bars; the only difference noted in all the testing with smooth bars was related to the fibering in the bar that resulted from prior thermomechanical history.

A drastic reduction in ductility was observed in Armco iron following compressive prestraining when the tests were carried out with notched bars. The reduction in area for bars tested in the axial orientation varied from 65% with no prestrain to approximately 0% after 63% compressive prestrain. In the transverse direction, over 80% compressive prestrain was required to drop the notched bar tensile ductility to 0 although in the unprestrained state the reduction in area was only 27%.

Prestraining caused two things to occur. The crystallographic texture was altered by prestraining such that the cleavage planes tended to become aligned perpendicular to the compression direction. Also, voids developed at the inclusion-matrix interface in the region of the equator of the particles if the stress direction is assumed to be polar. These voids did not form uniformly around the equator of the particles but formed in specific crystallographic orientations. With further strain they grew tunnel-like outward from the particle and eventually became flattened at their tip by the compressive strain. This configuration leads to local stress concentrations high enough to induce cleavage fracture in the notched bars.

The relative importance of these particle-initiated microcracks was shown by two techniques. Prestraining under pressue suppressed void and crack formation, but allowed crystallographic texture development. Prestrain embrittlement was almost completely eliminated with the limited hydrostatic pressures available, showing that the effect of texture was secondary to that of the particle-initiated voids and cracks.

Prestraining in the transverse direction subsequent to a prior prestraining in the axial direction restored a significant degree of ductility to the axial specimens embrittled by axial prestraining alone and reduced the reduction in area to 0 for transverse specimens whose ductility had been only moderately reduced by axial prestrain alone. Prestrain embrittlement in this iron is therefore primarily the result of the generation and growth of particle-induced microcracks. Modifying this embrittlement occurs by the closure and reorientation of these cracks.

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PUBLICATIONS

The results of this investigation are contained in detail in the Ph.D. thesis of one of the authors (WLB) which is on file at the Drexel University library. This should be on microfilm shortly. The title of the thesis is "Role of Second Phase Particles in Reducing the Retained Ductility of Wrought Materials".

A paper based on part of this material entitled, "The Role of Texture on Prestrain Embrittlement in Armco Iron" will be presented by Harry C. Rogers at the Fourth International Conference on Fracture, Waterloo, Canada, June 1977 and will be incorporated in the conference proceedings.

Three other papers based on this work are currently being written. Likely journals for publication are International Journal of Fracture, Metallurgical Transactions, Acta Metallurgica or Materials Science and Engineering.

PERSONNEL

The investigation reported herein constitutes the research portion of the requirements for the Doctor of Philosophy degree for Mr. William L. Brenneman and was carried out under the guidance of Dr. Harry C. Rogers, Professor of Materials Engineering, Drexel University.

Dr. Brenneman received his Ph.D. degree in June 1976.