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FINAL REPORT

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The effects of austenitizing and tempering on the fracture behavior and toughness of high carbon steels were investigated in martensitic specimens of AISI 52100 steel. Two levels of phosphorus content, 0.023 and 0.009 P, were evaluated. Specimens austenitized below Acm fractured primarily in a transgranular mode and showed slightly improved toughness, compared to the as-quenched condition, after tempering at 200°C. Higher temperature tempering resulted in reduced toughness before a substantial increase in

20. Abstract (continued)

toughness developed after tempering at 400°C and above. The effect of P was most pronounced in specimens tempered above 400°C, with the higher P specimens showing significantly lower toughness. Specimens austenitized above Acm failed primarily in an intergranular mode even in the as-quenched and low temperature-tempered specimens. Auger electron spectroscopy showed that the intergranular fracture was associated with thin carbide films that had apparently formed during quenching. Proeutectoid cementite grain-boundry allotriomorphy formation was stimulated by high P content. The prior austenite grain boundary carbide formation may not only cause the low toughness fracture at quenched and tempered specimens but may also be associated with the quench cracking frequently observed in high carbon steels.

TEMPERING AND FRACTURE BEHAVIOR OF HIGH CARBON MARTENSITE

by

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Introduction

This report summarizes the results of research performed during the period July 15, 1977 through August 14, 1980 under ARO sponsorship. The attached list of publications presents the accomplishments in the various major areas of emphasis in this period of support.

Two major groups of experiments were performed: the one concerned the effects of austenitizing temperature variations on the fracture toughness of quenched and tempered high carbon steel while the other concerned the effects of tempering on the microstructure and fracture of high carbon steels. The following sections briefly summarize results on each of the two major areas of research. Also included is a section on the scientific personnel involved in the research.

Effects of Austenitizing on Fracture

Experiments conducted by austenitizing above and below Acm showed that significant changes in fracture toughness and fracture morphology could be effected by control of austenitizing temperature. After austenitizing below Acm, fracture of quench and tempered high carbon steels occured in a transgranular mode. The associated fracture toughness was dependent on the distribution of micron-sized spherical particles residual after austenitizing. For widely dispersed particles, fracture toughness was high and for dense distributions of particles fracture toughness was significantly reduced because of the many sites for microvoid nucleation in the tempered martensitic microstructure.

Austenitizing above Acm resulted in complete solution of all carbide particles. The austenite transformed on cooling to microstructures of plate martensite and retained austenite, but the fracture was always intergranular along the prior austenite grain boundaries. Auger analysis showed that the intergranular fracture surfaces were associated with higher than bulk concentrations of phosphorus and carbide.

Sets of steels with identical compositions except for P content showed that the amount of intergranular fracture was increased by increased alloy P content. Also the amount of intergranular fracture increased with decreasing quenching rate. These observations led to the hypothesis that P segregation to austenite grain boundaries stimulated the formation of thin films of cementite during quenching which in turn was responsible for the low toughness, intergranular fracture.

The preceding hypothesis was supported by studies of the isothermal growth of cementite on 52100 steels containing 0.023 and 0.0099 P. The covering of austenite grain boundaries by cementite allotriomorphs was much more rapid on the steel with the higher P content. Other observations of isothermal cementite growth showed that growth essentially terminated at carbide film thicknesses much below those expected at equilibrium and that the growth mechanism was accomplished by the motion of ledges on coherent austenite-cementite interfaces.

Effects of Tempering on Fracture

Specimens of the 52100 steels with low and high phosphorus contents were systematically tempered at 50°C intervals after oil quenching from above (965°C) and below (850°C) Acm. The fracture characteristics were followed by testing of compact tension specimens, Charpy V-notch (CVN) specimens, and specimens with round notches. All fracture surfaces were examined in the scanning electron microscope. Peak loads for fracture initiation in CVN specimens were obtained by instrumented impact testing.

All sets of toughness measurements showed a slight increase in toughness over the as-quenched values when specimens were tempered at 200°C. Toughness decreased slightly when specimens were tempered between 250 and 400°C, and increased substantially when specimens were tempered above 400°C. The major effect of P developed only after tempering above 400°C, the high P specimens showing a much lower toughness. Fractography showed that large intergranular fracture features became more frequent as tempering temperature was increased. Light microscopy established that the apparent intergranular facets were related to coarse proeutectoid carbide networks that had formed during cooling after homogenization of the as-received steel plates.

Specimens austenitized at 965°C fractured largely in an intergranular mode in the as-quenched condition and even after tempering around 200°C. Auger electron spectroscopy (AES) showed high concentrations of carbon on the intergranular fracture facets and by characteristics of the AES carbon peaks provided evidence for the formation of thin carbide films on the prior austenite grain boundaries. Thus it appears that the conditions for the intergranular form of tempered martensite embrittlement in high carbon steels are met in as-quenched specimens and in specimens that are tempered at what are normally considered safe ranges for tempering on medium carbon steels. The formation of grain boundary carbides during quenching may also be a cause of the intergranular quench cracking that frequently occurs in high carbon steels during heat treatment.

There is a transition in fracture mode from intergranular to transgranular as specimens austenitized above Acm are tempered at successively higher temperatures. Transmission electron microscopy in a quenched and tempered Fe-1.2%C steel showed that cementite and/or chi-carbide formed as thin sheets along martensite plate-retained austenite interfaces as a result of tempering in the same range where the transition in fracture mode was observed in the AISI 52100 steel specimens. Thus it is possible that the formation of deleterious intragranular carbide distributions as a result of the second stage of tempering may be associated with the fracture transition.

Personnel

The principal investigator for this research was Dr. George Krauss. Two research assistants, Teiichi Ando and Deborah Yaney, were involved in the research over most of its duration. Mr. Ando received his M.S. degree in December, 1979. His thesis was based on research supported by the ARO. Ms. Yaney will complete the requirements for an M.S. degree in December, 1980. Again, ARO supported-research is the basis of her thesis. Both Mr. Ando and Ms. Yaney presented papers based on their research at the 1980 Annual Meeting of AIME last winter. Also involved in the characterization of the fine structure of changes during tempering during the summer of 1979 were Dr. Che-bao Ma, a visiting scientist from the Institute of Nuclear Energy Research, Taiwan and Professor Donald Williamson, Department of Physics, Colorado School of Mines.

<u>List of Publications Prepared with ARO Support</u>

July 15, 1977 to August 14, 1980

1. "The Microstructure and Fracture of a Carburized Steel," G. Krauss, Metallurgical Transactions A, Vol. 9A, 1978, pp. 1527-1535.*

2. "Martensite and Fracture in 52100 Steel," Kozo Nakazawa and G. Krauss, Metallurgical Transactions, Vol. 9A, 1978, pp. 681-689.*

3. "Determination of Small Amounts of Austenite and Carbide in Hardened Medium Carbon Steels by Mossbauer Spectroscopy," D.L. Williamson, R.G. Schupmann, J.P. Materkowski and G. Krauss, Metallurgical Transactions A, Vol. 10A, 1979, pp. 379-382.

4. "A Study of the Early Stages of Tempering in an Fe-1.2%C Alloy," D.L. Williamson, K. Nakazawa and G. Krauss, Metallurgical Transactions A, Vol. 10A, 1979, pp. 1351-1363.

5. "Fracture of High-Carbon Martensitic Steel," H.K. Obermeyer, T. Ando and G. Krauss, Proceedings International Conference on Martensitic Transformations, ICOMAT-79, Cambridge, Mass., June 24-29, 1979, pp. 732-737.

6. "Intergranular Fracture of a Carburized Steel," H.K. Obermeyer and G. Krauss, Proceedings of the 18th International Conference on Heat Treatment of Materials (ICHTM), American Society for Metals, Metals Park, Ohio, 1980, pp. 209-224.

7. "Toughness and Intergranular Fracture of a Simulated Carburized Case," H.K. Obermeyer and G. Krauss, to be published in Journal of Heat Treating.

8. "The Isothermal Thickening of Cementite Allotriomorphs in AISI 52100 Steel," by T. Ando, M.S. Thesis, Colorado School of Mines, December, 1979.

9. "The Isothermal Thickening of Cementite Allotriomorphs in a 1.5Cr-1C Steel," T. Ando and G. Krauss. Accepted for publication in Acta Metallurgica.

10. "The Effect of Austenitizing on Microstructure and Fracture of Hardened High Carbon Steels," G. Krauss. Proceedings of Conference on <u>Wear and Fracture Prevention</u> ASM, Peoria, Illinois.

11. "The Effect of Phosphorus Content on Grain Boundary Cementite Formation in AISI 52100 Steel," with Teiichi Ando, submitted to Met Trans A.

*Published in this period, but with earlier ARO support.