

A STUDY OF THE STRUCTURE AND MECHANICAL PROPERTIES OF ORDERED ALLOYS

Final Report

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April 1, 1969 - March 31, 1974

PREPARED FOR RESEARCH AND DEVELOPMENT DIVISION, OAK RIDGE OPERATIONS OFFICE
U. S. ATOMIC ENERGY COMMISSION
UNDER CONTRACT NO. AT-(40-1)-3908

I. Summary of Objectives and Results of Research Program.

The original objective of the research program was to elucidate the various strengthening mechanisms in alloys containing both local and long range order. It was recognized that much of the published work relating order and physical properties (in particular mechanical properties) was based on incomplete or ambiguous information regarding the microstructure of ordered alloys. For this reason a large portion of the work was based on a thorough characterization of microstructural parameters of various ordering systems subjected to thermal-mechanical treatments and the changes produced by deformation. Those parameters considered most important were: (i) local order in the matrix (ii) degree of long-range order (LRO) within a particular phase (iii) local variations in LRO (i.e. modulations) (iv) density and distribution of ordered phases (v) type, density and distribution of order-domain boundaries. The primary techniques of investigation were x-ray diffraction transmission electron microscopy and field-ion microscopy.

Much of the work was performed on neostructural alloys which change crystal systems and undergo lattice parameter changes as a function of the degree of order (e.g. Ni_4Mo and CuPt). It was found that the accompanying strains played a very important role not only in the kinetic and mechanistic behavior of the order transformation but also in the resulting mechanical strength. In both Ni_4Mo and CuPt isothermal ordering was found to produce duplex microstructures consisting of a homogeneous component within the grains and a heterogeneous component at the grain boundaries, both of which contribute to the transformation in varying amounts depending on the temperature. The homogeneous component was found to consist of fine, contiguous, partially ordered domains which could be viewed as the product of either

fine-scale nucleation and growth or continuous ordering. Kinetic studies showed that this transformation can be described in terms of a continuous ordering model when both strain and order modulations are considered. Stress ordering experiments further emphasized the significance of ordering strains by showing that pre-loads could influence the preferential formation and growth of certain variants (domains). This portion of the work clearly shows the transformation product in some systems cannot be accounted for by simple "quasi-chemical" ordering models.

The long-standing question of the "micro-domain" model for short range order was investigated by means of three-dimensional x-ray diffuse scattering measurements. This technique permitted more accurate separation and analysis of local order and size effect parameters. It was found that SRO in this system was best described in terms of rod-like features of Mo atoms aligned in $\langle 100 \rangle$ directions. While this configuration bears some similarity to that of fully-ordered Ni_4Mo it does not represent a clearly-defined picture of "ordered islands". This indicates that the micro-domain model is an oversimplified concept.

The mechanical properties of neostructural ordered alloys was found to be very much dependent on lattice strain and interface strain at order twin boundaries. A direct relationship was found between yield strength strain measured by x-ray line profile analysis. The geometric constraints of lattice periodicity also affect the mechanical properties as expected through their influence on the available shear systems. Deformation twinning was found to occur with relative ease in CuPt although this is generally regarded as an unlikely deformation mode in order structures. Analysis of atomic configurations shows that the usual partial twinning shears may operate in certain variants and preserve the ordered structure while re-orienting the

lattice. The net result is that the geometric restrictions on slip imposed by ordering may, in fact, enhance twinning.

Recent work (nearing completion) on two-phase non-stoichiometric Ni_4Mo alloys deal with the mechanical properties of age-hardening via ordered precipitates. Variations in flow stress with temperature indicate that misfit strain is again an important contribution to the overall strength. In the microstructure range where particle shearing occurs, APB energy also contributes.

The preceding paragraphs summarize ^{the} most important contributions of the program to the state of knowledge of the microstructure and mechanical behavior of ordered alloys. The work dealt for the most part with room temperature tensile behavior of stoichiometric alloys. It is suggested that this type of work be extended to include the following: (a) non-stoichiometric alloys of varying volume fractions, particle sizes and temperatures, (b) cyclic loading conditions and (c) elevated temperatures, (d) ternary alloying additions.

In addition to the above contributions of the program to the state of knowledge in the field, subsidiary developments of techniques and analysis also evolved during the course of the work. One of these was an analytical technique for calculating the LRO parameter from x-ray data for alloys of preferred domain orientation (LeFevre and Starke, Advances in X-ray Analysis, vol. 12) was used in the order kinetics study. Another was the use of field-ion microscopy techniques in the study of domain sizes beyond the resolution capability of transmission electron microscopy. A review on the past use and potential of this technique in the study of ordered alloys was published during this work.

II. Publications

B. Chakravarti, E. A. Starke, Jr., B. G. LeFevre, "Order-Induced Strengthening in Ni_4Mo ", Jour. Mat. Sci., **5**, (1970) 394-406.

Fu-Wen Ling, and E. A. Starke, Jr., "Correlation of Measured and Theoretically Calculated Microstrains in Deformed F.C.C. Metals", J. Appl. Cryst., vol. 3, (1970).

Fu-Wen Ling and E. A. Starke, Jr., "The Disorder-Order Transformation In Ni_4Mo ", Advances in X-ray Analysis, vol. 15.

Fu-Wen Ling and E. A. Starke, Jr., "The Development of Long-Range Order and The Resulting Strengthening Effects In Ni_4Mo ", Acta Met. vol. 19, (1971).

Fu-Wen Ling and E. A. Starke, Jr., "The Kinetics of Disorder-Order Transformations", Scripta Met., vol. 5, (1971) pp. 741-748.

F. Ling J. Collado and E. A. Starke, Jr., "An Internal Friction Study of Ni_4Mo ", Scripta Met., vol. 6, (1972) pp. 307-310.

K. C. Chen, Fu-Wen Ling and E. A. Starke, Jr., "Structure and Mechanical Properties of Stress-Ordered Ni_4Mo ", Mat. Sci. Eng., **13** (1974) pp. 255-262.

B. Chakravarti, C. J. Sparks, Jr., E. A. Starke, Jr., Robin O. Williams, "Short Range Order and the Development of Long Range Order in Ni_4Mo ", to be published.

R. Mitchell, H. G. Paris, and B. G. LeFevre, "Order Hardening in Equiatomic CuPt", Met. Trans. vol. 4, (1973).

B. G. LeFevre and E. A. Starke, Jr., "Changes in the Bragg-Williams Parameter with Deformation in Ordered Au_4V ", Adv. in X-Ray Analysis, vo. 12 (1969).

H. G. Paris and B. G. LeFevre, "Deformation Twinning in Ordered CuPt", Mat. Res. Bull., vol. 7, (1972) pp. 1109-1116.

B. G. LeFevre, "Field-ion Studies of Microstructures and Transformations In Long-range-ordered Alloys", Surf. Sci., vol. 23, no. 1, (1970) pp. 144-159.

J. G. Goodrum and B. G. LeFevre, "Strengthening Effect of Ordered Precipitates in a Ni-Ni₄Mo", in preparation.

III. Graduate Degrees.

B. Chakravarti, "Order Strengthening in Nickel - 20 Atomic Percent Molybdenum Alloy, M.S. Thesis, June 1970.

F. Ling, "The Determination of Microstrains and Antiphase Domain Size Produced During Ordering of a Ni₄Mo Single Crystal", Ph.D. Thesis, December 1970.

K. C. Chen, "Structure and Mechanical Properties of Stress-Ordered Ni₄Mo", M.S. thesis, January 1973.

B. Chakravarti, "Short Range Order of Long Range Order in Nickel - 20 Atomic Percent Molybdenum Alloy", Ph.D. Thesis, June 1973.

R. Mitchell, "A Study of the Ordering Transformation of Equiatomic Copper - Platinum", M.S. Thesis, May 1972.

Henry Paris, "Deformation Mechanism in Ordered CuPt", M.S. thesis, in progress.

John Goodrum, "The Strengthening Effect of Ordered Precipitates in a Ni-Ni₄Mo System", in progress, Ph. D. thesis.