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FINAL REPORT

**Novel Concepts in Weld Science:
Role of Gradients and Composite Structure**

Submitted to:

**Basic Energy Sciences Division
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Submitted by:

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Abstract

The effects of compositional and microstructural gradients on weld metal and simulated weld metal properties were evaluated in this multi-part study. The results obtained on single phase solid solution systems were used as a basis for a fundamental study of the effects of compositional gradients on crack growth, both at low temperatures, in fatigue and at high temperatures during creep. Methods to physically simulate gradients in weld metals with roll bonded laminate composites were applied to analyses of ferrite-austenite and ferrite-sigma-austenite multiphase systems. Finally, results of the physical simulation analyses were utilized to predict the effects of weld process parameters on weld metal properties.

1.0 INTRODUCTION

Weldments represent complex heterogenous materials which contain gradients in composition, microstructure and properties. These gradients are the primary factors which differentiate weld metal properties from wrought materials. The nature of gradients in weld metal strongly depends on metal composition and thermal experience. The genesis of weld coring depends on microsegregation and the compositional profile depends on the amount of self homogenization during the welding thermal cycle and time and temperature of the post weld heat treatment. Analysis of the influence of gradients on weld properties and behavior allows a fundamental improvement in the ability to predict weld metal properties.

Within the DOE-BES research program at the Colorado School of Mines, the effects of microcompositional gradients on the microstructure and properties of weld metals, both actual and simulated, have been considered. These studies have considered the fundamentals of gradients and the effects of gradients on both low and high temperature mechanical properties, phase transformation, and weld metal properties. Analyses have included actual weld metals and materials with microstructures designed to simulate specific aspects of gradients in weld metals. The publications which have resulted from the DOE-BES research are summarized below:

Fundamentals of Gradients

D.L. Olson and D.K. Matlock, "Compositional Gradient Effects on Weldment Properties", in Weldability of Materials, ed. by R.A. Patterson and K.W. Mahin, ASM, Materials Park, OH, 1990, pp. 49-55.

D.L. Olson, G.R. Edwards, S. Liu and D.K. Matlock, "Non-Equilibrium Behavior of Weld Metal", IIW Document IX-1685-92, pp. 1-49, American Council, AWS, Miami, Fl. (1992), Welding in the World, 31 (2) (March/April), pp. 142-154 (1993).

Effects of Gradients on Low Temperature Properties

G.L. Berry, D.L. Olson, and D.K. Matlock, "Influence of Microcompositional Gradients on Stress Corrosion Crack Propagation", Mat. Sci. and Engr. A148, pp. 1-6 (1991).

A. Wahid, D.L. Olson, D.K. Matlock and J.J. Kelly, "Role of Compositional Gradients in Environmentally Promoted Weld Cracking", Proc. of ASM "Heat Materials Conference", pp. 447-452, ASM, Materials Park, Oh. (1991).

Effects of Gradients on High Temperature Properties

I.D. Choi, D.K. Matlock, and D.L. Olson, "The Influence of Composition Gradients on Tensile Properties of Weld Metal", Scripta Metallurgica, vol. 22, 1988, pp. 1563-1568.

W.S. Gibbs, S.H. Wang, D.K. Matlock, and D.L. Olson, "High Temperature Impression Creep Testing of Weldments", Welding Journal, vol. 64, no. 6, 1985, pp. 153s-158s.

M.A. Lisin, I.D. Choi, D.K. Matlock, and D.L. Olson, "A Composite Modeling Analysis of Creep Testing on Heterogeneous Materials", Welding Journal vol. 69, no. 4, 1990, pp. 159s-165s.

I.D. Choi, D.K. Matlock, and D.L. Olson, "Creep Behavior of Nickel Copper Laminate Composites with Controlled Composition Gradients", Met. Trans. vol. 21A, no. 9, 1990, pp. 2513-2520.

I.D. Choi, D.K. Matlock, and D.L. Olson, "Communication: Creep Behavior of Nickel-Copper Solid Solution Alloys Below 0.55 Tm", Met. Trans. vol. 21A, no. 9, 1990, pp. 2601-2604.

I.D. Choi, D.K. Matlock and D.L. Olson, "An Analysis of Diffusion Porosity in Copper-Nickel Composite", Mat. Sci. and Engr. vol. A124, 1990, pp. 115-118.

I.D. Choi, D.K. Matlock, and D.L. Olson, "Influence of Composition Gradients on Weld Metal Creep Behavior: An Analysis Based on Laminate Composites", Proc. Gatlinburg International Conference on "Recent Trends in Welding Research", May 14-18, 1989, ASM, Materials Park, OH, pp. 787-792.

S.H. Wang, D.K. Matlock, and D.L. Olson, "High Temperature Deformation and Fracture Behavior of Laminate Composite: The importance of Interdiffusion During Creep", Scripta Met. and Mat., vol. 27, 1992, pp. 35-40.

S.H. Wang, D.K. Matlock, and D.L. Olson, "Physical Simulation for the Creep Behavior of Solidified Weld Metal", Research proc. 3rd Intern. Conf. on Trends in Trends in Welding Research, June 1-5, 1992, Gatlinburg, Tn, ASM, Materials Park, Oh. (1992), pp. 605-609.

S.H. Wang, D.K. Matlock, and D.L. Olson, "An Analysis of the Critical Conditions for Diffusion Induced Void Formation in Laminate Composite", *Mat. Sci. and Eng.*, A167, (1993), pp. 139-145.

Effects of Gradients on Phase Transformation

J.A. Self, B.F. Carpenter, D.L. Olson and D.K. Matlock, "Phase Transformations and Alloy Stability in Fe-Mn-Ni-Cr-Al Weld Metal", Alternate Alloying for Environmental Resistance, edited by G.R. Smolik and S.K. Banerji, TMS-AIME, Warrendale, PA, 1987, pp. 37-45.

S. Liu, D.L. Olson and D.K. Matlock, "A Thermodynamic and Kinetic Approach in the Development of Expressions for Alloy Behavior Prediction", *Journal of Heat Treating*, vol. 4, no. 4, 1986, pp. 309-316.

B.J. Carpenter, D.L. Olson, and D.K. Matlock, "Microstructural Characterization of Aluminum Passivated Stainless Steel Weld Metal Microstructure", *Microstructural Science*, vol. 14, Welding, Failure Analysis and Metallography, ed. by M.R. Louthan, I. LeMay, and G.F. VanderVoort, ASM, Metals Park, Ohio, 1987, pp. 137-158.

B.F. Carpenter, D.L. Olson, D.K. Matlock and M.J. Cieslak, "Phase Stability of Fe-Al-Cr-Ni Weld Metal", *Mat. Sci. and Engr.*, vol. A147, 1991, pp. 1-8.

D.L. Olson and D.K. Matlock, "Weld Metal Phase Stability", in *The Metal Science of Joining*, ed. by M.J. Cieslak, J. Perepezko, S. Kang, and M.E. Glicksman, TMS, Warrendale, PA, 1992, pp. 135-139.

J.S. Ogborn, D.L. Olson, and M.J. Cieslak, "Phase Stability Prediction of Solidification Microstructure for Modified Nickel Alloys", to be submitted to *Welding Journal* (1994).

D. Wenman, D.L. Olson, and D.K. Matlock, "Sigma Phase Formation Kinetics in Stainless Steel Laminate Composite", to be presented at AWS 1994, Philadelphia, PA.

Weld Metal Science

D.L. Olson, "The Fundamentals of Welding Consumables", *Proc. Gatlinburg Intern. Conf. on "Recent Trends in Welding Research"*, May 14-18, 1989, ASM, Materials Park, OH, pp. 553-562.

D.L. Olson and T.A. Siewert, "Present Consumable Technology Advances into the 21st Century", *Welding Journal*, vol. 69, no. 11, 1990, pp. 37-40.

T.A. Siewert, C.N. McCowen, and D.L. Olson, "Ferrite Number Prediction for Stainless Steel Welds", *Ferrous Alloy Weldments*, *Key Eng. Mats.*, vol. 67-70, pp. 149-166, *Trans. Publ.*, Zurich, Switzerland (1992).

T.A. Siewert, C.N. McCowan, and D.L. Olson, "Ferrite Number Prediction to 100 FN in Stainless Steel Weld Metal", *Welding Journal*, 67 (12) (1988), 289s-298s.

C.N. McCowan, T.A. Siewert, and D.L. Olson, "Stainless Steel Weld Metal: Prediction of Ferrite Content", *Welding Research Council Bulletin*, #342 (April 1989).

S.K. Marya and D.L. Olson, "Effect of Minor Elements and Process Parameters on GTA Weld Bead Variances in Steels", *Revue de Me'tallurgie, Memoires et Etudes Scientifiques*, 86 (1) (1989), pp. 25-34.

A. Wahid, D.L. Olson, D.K. Matlock, and C.E. Cross, "Corrosion of Weldments", *ASM Handbook*, 10th Edition, 6, pp. 1065-1069, ASM, Materials Park, OH (1993).

E.I. Kivineva, D.L. Olson, and D.K. Matlock, "Particulate Metal Matrix Composite as a Weld Deposit", submitted to *Welding Journal*, (1994).

M. Holt, D.L. Olson, and C.E. Cross, "Interfacial Tension Driven Fluid Flow Model for Hot Cracking", *Scripta Met. et Mat.*, vol. 26, 1992, pp. 1119-1124.

D.D. Kautz, D.L. Olson, P. Burgardt, G.R. Edwards, "A Characterization of Pulsed Electron Beam Welding Parameters", *Welding Journal*, vol. 70, no. 4, 1991, pp. 100s-105s.

D.L. Olson, R. Dixon and A.L. Liby (Editors), Welding-Theory and Practice, Materials Processing Theory and Practices Series, 8, ISBN: 0-444-87427-5 (TS227.W4154), pp. 1-389, North Holland Physics, Elsevier Science, NY, NY (1989).

D.L. Olson and T.A. North (Editors), Ferrous Alloy Weldments, 13 Chapters, ISBN: 087849-544-4, pp. 1-415, Trans. Tech. Publications, Ltd., Zurich, Switzerland March (1992).

D.L. Olson, T.A. Siewert, S. Liu, and G.R. Edwards, ASM Handbook: Welding and Joining, 10th edition, vol. 6, pp. 1-1299, ISBN: 077170-382-3, ASM, Materials Park, OH (1993).

G.M. Campbell, J.W. Elmer, W.S. Gibbs, D.K. Matlock, and D.L. Olson, "Evaluation of Factors Controlling High Temperature Service Life of 2 1/4 Cr-1 Mo Steel to Austenitic Stainless Steel Weldments" (ASM), *Trends in Welding Research in the United States*, New Orleans, LA, pp. 443-470, Materials Park, Ohio, November (1981).

J.W. Elmer, D.L. Olson and D.K. Matlock, "Thermal Expansion Characteristics of Austenitic Stainless Steel Filler Metals", *Welding Journal*, 61 (9) (1982), pp. 293-301s.

R.K. Okagawa, R.D. Dixon, and D.L. Olson, "The Influence of Nitrogen from Welding on Stainless Steel Weld Metal Microstructures", *Welding Journal*, 62 (8) (1983), pp. 204s-209s.

J.A. Self, D.K. Matlock, and D.L. Olson, "An Evaluation of Austenitic Fe-Mn-Ni Weld Metal for Dissimilar Metal Welding", *Welding Journal*, 63 (1984), pp. 282s-288s.

J.A. Self, S.A. Abdulgader, and D.L. Olson, "The Fe-Ni-Mn-Cu-C Filler Metal System for Welding Ductile Cast Iron", *Welding Journal*, 64 (11) (1985), pp. 322s-326s.

Ph.D. Theses

Joel A. Self (1987), T-3144, "Effects of Composition Upon the Martensitic Transformation Temperature of Austenitic Steel Weldments"

Bernard Frank Carpenter (1989), T-3557, "New PHACOMP of the Phase Stability of Fe-Al-Cr-Mn-Ni Weld Metals"

Abdul Wahid (1992), T-4241, "Cracking Behavior of Chemically Nonhomogenized Alloys"

Shing-Hoa Wang, (1992), T-4250, "Physical Simulation of High Temperature Creep in Systems with Dynamic Concentration Gradients"

Il-Dong Choi, (1989), T-3699, "Influence of Composition Gradients on Weld Metal Creep Behavior: An Analysis Based on Laminate Composites"

M.S. Theses

John Elmer (1981), T-2520, "The Thermal Expansion Characteristics of Stainless Steel Welds".

Glenn Campbell (1981), T-2486, "The Heat Affected Zone Microstructure of 2 1/4 Cr-1 Mo Steel from an In-Service Dissimilar Metal Weld"

Robert Kaichi Okagawa (1984), T-2388, "The Nitrogen Effect on Type 304L Austenitic Stainless Steel Weld Metal Welded with GTA System Under Ambient and Hyperbaric Conditions.

Bernard Frank Carpenter (1985), T-3118, "A Diagram to Predict Aluminum Passivated Stainless Steel Weld Metal Microstructure".

Stanley W. Pierce (1993), T-4037, "Thermocapillarity and Arc Phenomena in Stainless Steel Welding".

Saleh A. Abdulgader Sed (1983), T-2789, "The Behavior of the Iron-Nickel-Manganese-Copper Consumables System for Welding Ductile Iron".

Douglas D. Kautz (1987), T-3300, "Characterization and Morphology of Pulsed Electron Beam Welding on Type 31-6-9 Stainless Steel"

Christopher Nelson McCowan (1987), T-3349, "Cryogenic Strength, Toughness and Ferrite Content of Stainless Steel Welds"

Jonathan S. Ogborn (1988), T-3625, "An Examination of the Solidification Behavior and Microstructural Evaluation in Nickel Base Alloys"

Gerald L. Berry, Jr. (1988), T-3640, "Compositional Gradient Effects on Stress Corrosion Cracking Behavior of Weld Metal"

Clay Lawrence Taylor (1991), T-4060, "The Effect of Weldability of Alloy JBK-75 with Various Filler Metal Wire Additions"

Esa I. Kivineva (1991), T-4108, "Particulate Metal Matrix Composites as a Weld Deposit".

Kirk Arthur Lindahl, (1993), T-4028, "Alloy Phase Analysis from Measurements of Bulk Electronics and Magnetic Properties".

Mark Lisin (1989), T-3687, "Impression Creep Testing Within a Microstructural Gradient"

This report outlines in the following sections, the results from these studies on fundamental effects of gradients.

2.0 RESULTS OF COLORADO SCHOOL OF MINES DOE-BES RESEARCH ON MICROSTRUCTURE AND COMPOSITION GRADIENTS IN WELDMENTS

2.1 Influence of Solidification

Weld metal consists of cored microstructures. On cooling through the two phase (liquid/solid) field, a compositional profile in the liquid ahead of the liquid/solid interface develops. The profile is controlled by solute diffusion and the magnitude of the solute partitioning coefficient, k , and the composition of the solute in the liquid adjacent to the liquid/solid interface is given by C_0/k , where C_0 is the average bulk composition. As solidification in the weld pool progresses and the neighboring dendrites thicken and approach each other, the last interdendritic liquid to solidify can have a solute composition approaching $2C_0/k$. The final weld metal compositional profile will result from the self homogenization of these solidification promoted interdendritic solute segregation.

The primary difference between weld metal and wrought alloys is the microsegregation due to solidification which has major influence on the sequential phase transformations which generate the microstructural features that control properties. Major improvements in welding consumables and practice could be more effectively made if there were a fundamental understanding of behavior of chemically nonuniform material (1-3). The long range intended use of this research is to provide a fundamental foundation for significant improvements in our ability to predict weld metal properties. To achieve a basic understanding of the influence of compositional gradients, simulated weld metal has been produced by lamination of solid solutions through roll bonding and annealing and through the use of directionally solidified binary alloy castings and single crystals. These analytical approaches remove some of the complex and nonoriented features of the weld metal.

2.2 Phase Transformations in Cored Structures

Weld metal, which possesses a solidification structure, consists of localized variations in alloy compositions that influence the formation of second phases (4). The influence of the solidification structure can be realized by considering an element such as oxygen in ferritic steel welds. The oxygen concentration at solidification of the interdendritic liquid can be over 10,000 ppm instead of the 300 ppm average composition determined analytically from bulk chemical analyses. The locally high oxygen concentrations cause major perturbations to the interdendritic pyrochemistry, and as a result, non-metallic inclusions are found aligned in the interdendritic regions of the weld metals.

Furthermore, their compositions, concentrations and size distributions are strongly influenced by these perturbations (5). In addition, non-metallic inclusions affect weld metal phase transformations. The type, amount and size distribution of inclusions, if adequately controlled, can assist in the development of improved weld microstructures and properties (6).

The influence of coring in high alloys on the topological closed phase formation has also been investigated. Ogborn (7) demonstrated that the "New Phacomp" analysis of Cieslak et al. (8) applies for the prediction of weld metal TCP formation. Carpenter et al. (9) extended this "New Phacomp" analysis to include the influence of post weld heat treatment on weld metal phase stability. Martensite formation is also influenced by localized compositional variations. For both the as welded and fully homogenized weld metals, Self et al. (10) reported M_s equations which can be used over broad compositional ranges.

2.3 Effects of Gradients on Weld Metal Mechanical Properties

The influence of compositional gradients on both brittle and ductile cracking behavior was investigated. The brittle cracking which occurs with minimal dislocation

movement was studied using stress corrosion cracking (11). The ductile cracking behavior was studied using the localized plasticity resulting from fatigue testing (12). Both studies used weld simulated specimens which aligned the coring or laminated structure such that the cracks selectively propagated through a range of compositional gradients.

2.3.1 Brittle Cracking in Simulated Weld Metal

Analysis of stress corrosion cracking in a fully austenitic stainless steel casting with various homogenizing heat treatments was used to investigate brittle cracking behavior (11). These heat treatments produced a series of specimens with different compositional gradients in their cored structure. If the controlling mechanism for stress corrosion crack growth is anodic dissolution, the crack should propagate through the localized region of least corrosion resistance (i.e. most anodic). This region is likely to have a lower content of passivating elements. In this investigation the crack was found to propagate where the chromium content had the steepest compositional gradient in the cored solidified structure (11). This cracking behavior is consistent with an interfacial energy-sensitive SCC model which had been modified with the Cahn-Hilliard concepts (13) for influence of compositional gradients. The results of this investigation (11) and the use of the Cahn-Hilliard non-uniform thermodynamic concepts to explain the cracking behavior offer significant insight into other brittle cracking behaviors where compositional gradients are present, e.g. liquid metal embrittlement.

2.3.2 Ductile Cracking in Simulated Weld Metal

An investigation of fatigue crack propagation in compact tension fatigue specimens, which were specially prepared from oriented very large grained copper-nickel castings and copper-nickel single crystals, was performed (12). These specimens were

also homogenized to different degrees to produce samples with different compositional gradients.

Fatigued specimens were analyzed with metallography, elemental microprofiling, fractography, and transmission electron microscopy, and the results showed that fatigue crack propagation preferentially followed locations with the steepest compositional gradients. The fatigue crack growth rates were also measured to determine the influence of the compositional gradients. Transmission electron microscopy indicated that the size of dislocation cells in regions adjacent to the crack in fatigued specimens is influenced by the compositional gradient. The dislocation cell size was significantly larger in specimens in the as-cast condition compared to samples which were fully homogenized. Limited hardness testing also indicated that plastic deformation occurs to different degrees in the as-cast single crystal specimens compared to homogenized specimens. These results raised a number of important questions with respect to the effects of gradients on fatigue crack growth and on plastic deformation.

2.4 The Effects of Dynamic Compositional Gradients on the Creep Behavior of Weld Metal

The effects of microstructural and compositional gradients on high temperature mechanical properties of weldments have been considered in several studies. Analysis of the impression creep behavior across austenitic to ferritic steel dissimilar metal weldments showed that the minimum in creep resistance occurs in a zone adjacent to the fusion line where creep cracking has been observed in service (14). Impression creep behavior across beads in multipass low carbon steel weld metal showed that the grain refined heat affected zone exhibited lower creep resistance than either as-solidified or reheated as-solidified beads. The lower creep resistance in weld metal was found by

these measurements but it is difficult to achieve a mechanistic understanding due to the presence of complex and nonoriented compositional and microstructural gradients.

To provide a material with a simplified gradient for impression creep analysis, Lisin et al. (15) evaluated the impression creep behavior across a roll bonded interface between copper and a copper-zinc solid solution alloy. The observed creep rates varied significantly with position on a traverse across the interface and correlated with predictions based on a composite model which considered deformation to be concentrated to a zone below the impression creep punch.

Choi et al. (16-20) extended the composite analysis of Lisin et al. (15) to a study of the tensile creep behavior of weld metals and laminate composites with controlled composition gradients. The effects of weld metal microsegregation, as altered by post-weld heat treatments, on high temperature creep properties were investigated on Monel alloy 400 (Ni-Cu alloy) weld metal (16,20). All weld metal tensile samples were machined from single pass GTA welds and were heat treated in vacuum in the range of 600°C to 1000°C to produce samples with different composition gradients. Long-time constant load creep tests were performed at 500°C. The steady state creep rates decreased with a decrease in the amplitudes of composition gradients. The deformation behavior of the solidified dendritic weld metal microstructure was modeled based on results obtained on laminate composites of nickel and copper. A roll bonded laminate composite with forty 20 micron thick layers of each material was chosen to simulate the continuous variations in local composition gradients existing at the cored dendrites in as-solidified weld metal. The laminates were annealed to produce controlled composition gradients with dimensions equivalent to those observed in the weld metal. With an increase in heat treatment time (i.e. a decrease in the composition gradient amplitude) the laminate composite steady state creep rates decreased and correlated directly to a model based on the rule of mixtures when the layer properties were based on the

average layer compositions. This investigation was performed at a temperature where there was no apparent change in the localized compositional profile during the length of the creep test, and thus, the creep process was unaffected by interdiffusion between the layers.

To evaluate the effects of interdiffusion during deformation on the high temperature mechanical properties of materials with dynamically unstable microcompositional gradients were considered by Wang et al. (21,22) in their study of the high temperature creep behavior of roll bonded laminate composites with alternating 21 μ m layers of nickel and Ni-Cu solid solution alloys (with copper concentrations between 9 and 48 at. pct. Cu). All tests were performed on materials in the as-rolled condition. The composition couples were chosen to span the range where significant interdiffusion would occur during high temperature creep testing but would not lead to interfacial Kirkendall void formation. Creep tests were performed in the temperature range of 577 to 700°C at stress levels between 30 and 104 MPa. The creep curves were analyzed to determine the effects of layer composition and interdiffusion on curve shape and creep rate at a given time. The creep rates demonstrated nonlinear behaviors with composition, behavior which was dependent on the coring amplitude as measured with energy dispersive spectroscopy (EDS). The deformation behavior can not be described by analyses based on a simple rule of mixtures. Observed deviations from conventional behavior which result from changes in the microcompositional gradients were considered in conjunction with an analysis of creep mechanisms. When the results were analyzed in terms of classical power law creep rate law and compared results with the literature, the observed changes in n and Q suggest various controlling mechanisms.

The apparent controlling mechanism depends on the microsegregation amplitude and wavelength, environmental temperature, and the applied stress. At low stress and high temperature (e.g. 700°C), creep is dominated by thermally activated deformation or

short-circuit diffusion. At moderate stresses and medium temperatures (e.g. 627 to 664°C), creep is apparently dominated by lattice diffusion assisted climb. At high applied stresses and low temperatures (e.g. 577°C), creep appears to be dominated by the effects of a thermal excess vacancies to enhance atomic mobility.

2.5 Composite Weld Deposit

An investigation was performed to study the fundamentals associated with the production of particulate metal matrix composite weld deposits in which the weld deposit would have a high volume fraction of uniformly distributed insoluble ceramic or refractory metal particles (23). In this investigation weld deposits with austenitic stainless steel (AISI 310) base metal were produced and both gas metal arc and gas tungsten arc welding procedures were used to study the effects of the welding process on particle transfer and recovery. The effects of density and size of the particulates were determined using different powder materials. Tungsten (coated and uncoated), tungsten carbide, niobium carbide and titanium carbide were selected for powder materials as they represented particulate materials with densities which were less than, equal to, or greater than the stainless steel matrix. Various particle size distributions were investigated ranging around an average size from 0.5 to 250 microns. This combination of materials and sizes allowed fluid flow and solidification particle entrapment models which consider the particle distribution in the solid matrix to be evaluated. Processing parameters for acceptable solidification of the weld deposits with second phase particulates were determined.

Weld deposits for each powder type and for both gas metal arc and gas tungsten arc welding processes were analyzed. The results demonstrated that particulate metal matrix composite weld deposits can be made and that the particles can be transferred through the arc into the weld pool. Particle dispersions can be controlled with proper

selection of powder material. The criterion for optimum powder material include particle size, type, density and composition. The tendency for particle suspension in the liquid weld pool was modeled using both fluid flow calculations and analytical predictions for the critical conditions where the particle is either entrapped into the solid or is dragged by the solid/liquid interface during solidification. These calculations satisfactorily predicted the behavior of a specific type and size of particle in the weld pool. Titanium carbide particulates with an average size of 1 μm were found to produce well distributed particles in the weld deposits and improved material properties. Thus, weld deposits can be engineered by using composite material design concepts.

An application for this kind of weld deposits would be in welded assemblies for high temperature service, such as components of heat exchangers and power plants. The creep resistance can be significantly improved by a homogeneous dispersion of second phase particles which can serve as effective obstacles to the dislocation motion increasing the creep resistance of the metal. When subjected to an external load, the particles tend also to carry a higher stress, thereby reducing the stress level experienced by the matrix. Thus, the creep resistance of particle reinforced alloys is improved by these two mechanisms: bypassing of the particles by dislocations and reduction of creep rate associated with the stress distribution.

2.6 The Formation and Growth of Sigma Phase in Ferrite-Austenite Laminate Material

Typical stainless steel welds contain between 5 and 10 percent delta ferrite to reduce hot cracking. Unfortunately, precipitation of sigma phase during use at temperatures between 600 and 900°C cause embrittlement problems. Special experiments were designed to study the kinetics of sigma phase precipitation.

Laminates with alternating layers of austenitic (304L and 316L) and ferritic (E-Brite) stainless steels were used to evaluate phase transformations which develop as a

result of interdiffusion. Sigma phase formation near the austenite-ferrite interface were analyzed and time-temperature-percent sigma phase precipitated diagrams for both composites were determined. The parabolic rate law and an error function analysis was used to extract elemental diffusion coefficients (D) responsible for the development of sigma phase. Values of D_{Cr} and D_{Ni} compared favorably with previously reported data, implying that nickel diffusion controls the growth of austenite into the ferrite material; subsequently the growth of sigma phase is controlled by chromium diffusion.

Knowledge gained from this research could be used to design welding electrodes and postweld heat treatment schedules to avoid sigma phase embrittlement. Also, composites heat treated to the optimum condition reduce tensile strengths higher than predicted by the rule of mixtures, which suggest that new austenite-ferrite stainless steel laminate materials offer improved properties and potentially a new class of high strength stainless steels.

3.0 SUMMARY OF ACCOMPLISHMENTS

1. Laminate composites of pure nickel and Ni-Cu solid solutions alloys have been fabricated and shown to exhibit predicted properties with respect to porosity formation during high temperature.
2. Creep data in laminate composites have been obtained as a function as a function of stress and temperature and have shown to depend on the dynamic concentration gradients which develop during creep. Observed changes in the stress exponent and activation energy for creep are interpreted to reflect changes in controlling deformation mechanisms as a result of interdiffusion.
3. Techniques for evaluating the fine interlayer microstructures in laminate composites have been developed and the resulting dislocation structures in crept specimens have been evaluated in a study performed jointly with the transmission electron microscopy groups at the National Renewable Resources Laboratory and Oak Ridge National Laboratory.
4. Observed decreases in the resistance to high temperature fracture with an increase in layer thickness in laminate composites were interpreted to reflect the effects of interfacial stress redistribution and the wavelength dependence of interdiffusion during creep.
5. The basics of an FEM analysis of creep in laminate composites have been identified, and analyzed with NIKE2D.
6. Fatigue cracks propagate through regions of steep compositional gradients in cored material. Fatigue cracks have been characterized in both directional solidified copper-nickel castings and copper-nickel single crystals. Significant differences in dislocation cell structures were observed adjacent to the fatigue cracks in all cast and annealed alloy single crystals.

7. The concept of using metal matrix composite weld deposits as a method to design advanced weldments was demonstrated. The physical conditions to achieve a high volume fraction of second phase with a proper particle distribution was identified. Fluid mechanical and solidification modelling was performed to assist in the selection of powder materials which would guarantee excellent particle distribution in the MMC weld deposit.

4.0 HONORS

Adams Lecture, AWS, 1984, "Prediction of Austenitic Weld Metal Microstructure and Properties", D.L. Olson.

McKay Helm Award, AWS, 1985, "An Evaluation of Austenitic Fe-Mn-Ni Weld Metal for Dissimilar Metal Welding", by J.A. Self, D.K. Matlock, and D.L. Olson.

Charles H. Jennings Memorial Award, AWS "A Composite Modeling Analysis of Creep Testing on Heterogeneous Materials", by M.A. Lisin, I.D. Choi, D.K. Matlock, and D.L. Olson.

5.0 REFERENCES

1. D.L. Olson and D.K. Matlock, "Compositional Gradient Effects on Weldment Properties", in Weldability of Materials, ed. by R.A. Patterson and K.W. Mahin, ASM, Materials Park, OH, 1990, pp. 49-55.
2. D.L. Olson, "The Fundamentals of Welding Consumables", Proc. Gatlinburg Intern. Conf. on "Recent Trends in Welding Research", May 14-18, 1989, pp. 553-562, ASM, Materials Park, Oh. (1990).
3. D.L. Olson and T.A. Siewert, "Present Consumable Technology Advances into the 21st Century", Welding Journal vol. 69, no. 11, pp. 37-40 (1990).
4. D.L. Olson, S. Liu, and G.R. Edwards, "Role of Solidification of HSLA Steel Weld Metal Chemistry", Proc. of Materials Weldability Symposium, TMS, Detroit, MI, October (1990), TMS-AIME, Warrendale, PA (1991).
5. R.H. Frost, D.L. Olson, and S. Liu, "Influence of Solidification on Inclusion Formation in Welds", Proc. 3rd Int. Conf. on Trends in Welding Research, Gatlinburg, TN, June 1992, ASM, Materials Park, OH (1992).
6. O. Grong and D.K. Matlock: "Microstructural Development in Mild and Low Alloy Steel Weld Metals", International Metallurgical Reviews, vol. 31, no. 1, 1986, pp. 27-48.
7. J.S. Ogborn, "An Examination of the Solidification Behavior and Microstructural Evolution in Nickel Base Alloys", CSM Thesis T-3625 (1988).
8. M.J. Cieslak, G.A. Knorovsky, T.J. Headley, and A.D. Romig, Jr., "The Use of New PHACOMP in Understanding the Solidification Microstructure of Nickel Base Alloy Weld Metal", Met. Trans., 17A (12), pp. 2107-2115 (1986).
9. B. F. Carpenter, D. L. Olson, D. K. Matlock and M. J. Cieslak, "Phase Stability of Fe-Al-Cr-Ni Weld Metal", Mat. Sci. and Engr., A147, pp1-8,(1991).
10. J.A. Self, B.F. Carpenter, D.L. Olson, and D.K. Matlock, "Phase Transformation and Alloy Stability in Fe-Mn-Ni-Cr-Al Weld Metal", Alternate Alloying for Environmental Resistance, pp. 37-45, TMS-AIME, Warrendale, PA (1987).
11. G. L. Berry, D. L. Olson, and D. K. Matlock, "Influence of Microcompositional Gradients on Stress Corrosion Cracking Propagation", Mat. Sci. and Engr. A148, pp 1-6 (1991).
12. A. Wahid, D. L. Olson, D. K. Matlock and J. J. Kelly, "Role of Compositional Gradients in Environmentally Promoted Weld Cracking", Proc. of ASM "Heat Materials Conference", pp 447-452, ASM, Materials Park, Oh. (1991).
13. J.W. Cahn, and J.E. Hilliard, "Free Energy of a Nonuniform System. I. Interfacial Free Energy", J. Chem. Phys., 28 (2), pp. 258-267 (1958).

14. W.S. Gibbs, S.H. Wang, D.K. Matlock, and D.L. Olson, "High Temperature Impression Creep Testing of Weldments", *Welding Journal*, vol. 64, No. 6, 1985, pp. 153s-158s.
15. M. A. Lisin, I. D. Choi, D. K. Matlock, and D. L. Olson, " A Composite Modeling Analysis of Creep Testing on Heterogeneous Materials", *Welding Journal* 69(4), 159s-165s (1990).
16. I.D. Choi, D.K. Matlock, and D.L. Olson. "The Influence of Composition Gradients on Tensile Properties of Weld Metal", *Scripta Metallurgica*, vol. 22, 1988, pp. 1563-1568.
17. I. D. Choi, D. K. Matlock, and D. L. Olson, "Creep Behavior of Nickel Copper Laminate Composites with Controlled Composition Gradients", *Met. Trans.* 21A(9), 2513-2520 (1990).
18. I. D. Choi, D. K. Matlock, and D. L. Olson, "Communication: Creep Behavior of Nickel-Copper Solid Solution Alloys Below 0.55 T_m", *Met. Trans.* 21A(9), 2601-2604 (1990).
19. I. D. Choi, D. K. Matlock and D. L. Olson, "An Analysis of Diffusion Porosity in Copper-Nickel Composite", *Mat. Sci. and Engr.* A124, 115-118 (1990)
20. I. D. Choi, D. K. Matlock, and D. L. Olson, "Influence of Composition Gradients on Weld Metal Creep Behavior: An Analysis Based on Laminate Proc. Gatlinburg International Conference on "Recent Trends in Welding Research", May 14-18, 1989, pp 787-792, ASM, Metals Park, Oh., (1990).
21. S. H. Wang, D. K. Matlock, and D. L. Olson, "High Temperature Deformation and Fracture Behavior of Laminate Composite: The importance of Interdiffusion During Creep", *Scripta Met. and Mat.*, 27, pp. 35-40 (1992).
22. S. H. Wang, D. K. Matlock, and D. L. Olson, "Physical Simulation for the Creep Behavior of Solidified Weld Metal", *Research, proc. 3rd Intern. Conf. on Trends in Trends in Welding Research* , June 1-5, 1992, Gatlinburg, Tn, ASM, Materials Park, Oh. (1992).
23. E. I. Kivineva, D. L. Olson, and D. K. Matlock, "Particulate Metal Matrix Composite as a Weld Deposit", submitted to *Welding Journal*, (1993).

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