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**CRADA FINAL REPORT
for
CRADA Number C/ORNL 92-0099**

**DEVELOPMENT OF Ni₃AL ALLOYS FOR
USE AS TRANSFER ROLLS IN HOT
PROCESSING OF STEELS**

M. L. Santella
R. McDonald

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**DEVELOPMENT OF Ni_3Al ALLOYS FOR USE AS TRANSFER
ROLLS IN HOT PROCESSING OF STEELS**

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Date Published: May 1996

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ABSTRACT

CRADA No. 92-0099

Metallamics

DEVELOPMENT OF Ni_3Al ALLOYS FOR USE AS TRANSFER ROLLS IN HOT PROCESSING OF STEELS

The purpose of this cooperative effort was to evaluate the potential of Ni_3Al alloys, such as IC221M and IC396M, for use as transfer rolls in heat treating furnaces and slab reheating furnaces used during the normal hot processing of steel ingots into rolled products. Rolls consist of three parts: the center tube section which forms the roll surface in direct contact with the steel, and the sections welded at each end of the tube, called trunnions, which bear the load. The work in this CRADA focused on weldments and base materials. The transfer rolls in the furnaces used in the hot processing of steel have been made, almost exclusively, from iron-chromium-nickel heat resistant alloys for over 35 years. The iron-based heat resistant alloys experience a variety of problems when exposed to temperatures above 760°C including: cracking, dimensional instability, and excessive oxidation. Many defects in rolled steel products can be traced directly to rolls used in the processing. Also the demand for higher quality products, spurred in part by competition from foreign producers, requires that various avenues for improving overall quality of rolled steel products be pursued. Initial work done by the Contractor and Metallamics indicated that Ni_3Al alloys may perform better than existing iron-chromium-nickel alloys do as transfer rolls in heat treating furnaces. The use of Ni_3Al may lead to rolls with longer operational life, improved high temperature oxidation resistance and mechanical properties, higher quality rolled steel products, and improved energy and operational efficiencies in the hot processing of steel. The goal of the work was to test Ni_3Al alloys for the transfer roll application in order to improve process efficiency, minimize waste by virtue of producing rolled steel of higher quality and to enhance the competitiveness of U.S.-based steel producers.

Metallamics operates as a supplier of products to U.S.-based steel companies (Bethlehem Steel Company, Inland Steel Company, Latrobe Steel Company, etc.), and they are interested in improving materials for and design of transfer rolls. The development of an improved material for the transfer rolls will have a significant favorable impact for U.S.-based steel producers, and it will help the Department of Energy (DOE) in meeting the goals of the National Energy Strategy through improved energy efficiency, decreased industrial process waste, and improved worldwide competitiveness of U.S. industry. This project began approximately October 1, 1992 and was completed on September 29, 1995. The total cost of the project was \$225,000, shared equally by the participants.

DISCLAIMER

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DEVELOPMENT OF Ni₃Al ALLOYS FOR USE AS TRANSFER ROLLS IN HOT PROCESSING OF STEELS

BACKGROUND

Traditionally, polycrystalline intermetallic compounds were viewed as perfect examples of brittle materials. Work over the last decade, however, demonstrated that the ductility and engineering properties of certain intermetallic compounds, like Ni₃Al, can be substantially improved through the application of physical metallurgy principles to these alloy systems. Depending on composition and processing, tensile elongations near 50% are reported for Ni₃Al alloys. Other desirable properties ascribed to Ni₃Al alloys include: (1) excellent resistance to air oxidation, especially in the temperature range of 800-1100°C; (2) excellent resistance to carburization in both oxidizing and reducing atmospheres up to 1100°C; (3) yield strength that increases with temperature and peaks in the range of 650-850°C; (4) good compressive yield strength in the temperature range of 650-1100°C; and, (5) excellent wear resistance at temperatures above 600°C. Because of such properties, Ni₃Al alloys are considered promising candidates for a range of structural applications which require the use of the materials in a variety of product forms including sheet, plate, tubing, piping, wire, castings, and as coatings. Currently, some of the most promising and well developed applications require the use of cast Ni₃Al alloys.

Nominal compositions of the two Ni₃Al alloys being evaluated most intensively for use in the cast condition are given in Table 1. Major alloying additions are Cr, Mo, and Zr. Chromium is added to prevent dynamic oxygen embrittlement at intermediate temperatures. Molybdenum is added as a solid solution strengthener, and its effectiveness is maintained both at ambient and elevated temperatures. Zirconium produces some strengthening, but it is added mainly for reducing porosity in castings.

Table 1. Nominal compositions of cast Ni₃Al alloys.

Alloy ID	Concentration, wt%				
	Ni	Al	Cr	Mo	Zr
IC221M	81.2	8.0	7.7	1.4	1.7
IC396M	80.5	8.0	7.7	3.0	0.8

PURPOSE OF COOPERATIVE PROJECT

The purpose of this cooperative research and development project with Metallamics was to evaluate the potential of Ni₃Al alloys, specifically IC221M and IC396M, for use as transfer rolls in heat treating furnaces and slab reheating furnaces used during the normal hot processing of steel ingots into rolled products. The transfer rolls in the furnaces used today are made, almost exclusively, from iron-chromium-nickel heat resistant alloys, and they have been for over 35 years. The iron-based heat resistant alloys experience a variety of problems when exposed to temperatures above 760°C including: cracking, dimensional instability, and excessive oxidation. In the past, shortcomings of the iron-chromium-nickel alloys were largely overlooked even though many defects in rolled steel products can be traced directly to them. Today, the demand for higher quality products requires that every possible avenue for improving overall quality of rolled steel products be pursued. Work done by the Oak Ridge

National Laboratory (ORNL) and Metallamics indicated that Ni_3Al alloys may perform better than existing iron-chromium-nickel alloys do as transfer rolls in heat treating furnaces. It is anticipated that the successful development and implementation of Ni_3Al alloys for the transfer roll application will improve both the quality of rolled steel products and the competitiveness of U.S. based steel producers.

In the context of this CRADA project, Metallamics operated as an agent for a consortium of U.S. based steel companies (Bethlehem Steel Co., Inland Steel Co., Latrobe Steel Co., etc.) to address improvements in materials for and design of transfer rolls. The development of an improved material for the transfer rolls will have a significant favorable impact for U.S. based steel producers, and it will help the Department of Energy (DOE) in meeting the goals of the National Energy Strategy through improved energy efficiency, decreased industrial process waste, and improved worldwide competitiveness of U.S. industry. This project began approximately on October 1, 1992, and was be officially completed on September 30, 1995

SCOPE OF WORK

This development program was divided into two phases:

Phase 1

The overall objectives of Phase 1 were: (1) to analyze the distribution of stresses in a roll under normal service conditions; and, (2) to evaluate the behavior of Ni_3Al base metal and weld metal under simulated roll service conditions.

The responsibilities of ORNL in Phase 1 were (1) to perform a study of the oxidation behavior of Ni_3Al base and weld metal under simulated service conditions; and, (2) to develop procedures, including joint design, for welding trunnions to rolls using Ni_3Al alloy weld filler metals.

In Phase 1, Metallamics agreed: (1) to use finite element techniques to describe the stress state of a Ni_3Al alloy heat treating roll under the stress and temperature conditions expected in service; and (2) to work with ORNL on the development of suitable joint designs.

Phase 2

The objectives of Phase 2 were: (1) to produce centrifugally cast tubes of Ni_3Al alloys for use as heat treatment furnace rolls; (2) to weld Ni_3Al trunnions to these tubes to form completed roll assemblies; and, (3) to test and evaluate the welded rolls under actual operating conditions in continuous heat treating furnaces.

In this phase, ORNL agreed: (1) to procure all necessary Ni_3Al materials including feedstock and welding consumables for at least one roll; (2) to arrange for the manufacture of cast rolls and trunnions of Ni_3Al alloy; (3) to provide welder training at the site of roll fabrication; (4) to provide technical assistance during welding of the initial test roll assemblies; and, (5) to perform microstructural analysis of roll body and weldment samples taken from rolls exposed to service conditions in a heat treating furnace.

The responsibilities of Metallamics in Phase 2 were: (1) to coordinate the installation of the assembled Ni_3Al alloy rolls in a continuous heat treatment furnace; and, (2) to provide, to ORNL, specimens of the

rolls, including base material and weldments, obtained during periodic inspections, at the end of their evaluation or after failure.

PROGRESS

October 1992-September 1993

November 17: A meeting was held in Livonia, MI, to review the status of previous technical work relevant to this CRADA project, to review the objectives of the CRADA, and to develop plans and schedules for performing its various tasks. Metallamics reviewed the service requirements for transfer rolls, and discussed their experiences with installing two Ni₃Al alloy rolls in a slab soaking furnace at the Nucor Steel Crawfordsville plant. The Nucor rolls failed at the weldments on their trunnions. However, they were in service long enough to indicate the possibility of increased service life compared to conventional roll materials. In addition to the welds, concern was expressed about limiting the amount of eutectic that occurs in the Ni₃Al alloy microstructures. Because the eutectic forms as a result of Zr microsegregation during solidification, it was agreed that proceeding on the CRADA with the alloy containing less Zr, IC396M, was desirable. Additional discussions centered on various configuration for attaching the roll shells to trunnions, and the importance of surface finish on the rolls.

April 7: Representatives of ORNL and Metallamics visited the Burns Harbor Plant of Bethlehem Steel Corporation. The purpose of the meeting was to explore the possibility of installing Ni₃Al alloy transfer rolls in a slab reheating furnace in a 160-in plate mill. The dimensions of the rolls are 14-in-diameter x approximately 1-in-wall x 13.5-ft-length. The rolls presently in use are fabricated by welding trunnions onto centrifugally cast roll shells. The mill general foreman outlined the types of problems encountered with conventional rolls, which included: scoring of the roll surfaces by the steel slabs, swelling of the roll bodies, and short service life. Bethlehem staff were impressed with the data package on the Ni₃Al alloys and were very agreeable to installing Ni₃Al rolls on a trial basis. They believed that Ni₃Al rolls offered the promise of reduced need for roll inspection, and, therefore, reduced furnace down time, improved product quality because of increased resistance to scoring, and longer service life. One result of this visit was the formulation of a plan for producing rolls, including potential sources for critical items such as melt stock, centrifugal castings, static castings for trunnions, welding wire, machining, welding and assembly.

April 22: Representatives of ORNL and Metallamics visited Sandusky International, Sandusky, Ohio, to discuss centrifugal casting of Ni₃Al alloy rolls. Sandusky International (SI) agreed to produce two centrifugal castings of the IC396M alloy. Plans were finalized for procuring the required melt stock (5500 lb total), and for procuring four statically cast trunnions from Alloy Engineering and Casting Company, Champaign, Illinois. Procedures were prepared for establishing a capability for performing chemical analysis of Ni₃Al alloys at SI. A production schedule was drafted including melting, casting, machining, and assembly of the rolls.

July 1: The first of two IC396M roll shells was centrifugally cast at Sandusky, Ohio. Representatives of ORNL, Metallamics, and SI were present. The Ni₃Al alloy heat was melted in an induction furnace under argon cover, and its chemistry was adjusted on-line to produce the IC396M composition. Actual casting proceeded without incident. The outside diameter of the roll shell had an excellent visual appearance with a normal surface finish for this type of casting. The casting was approximately 20 ft in length, and SI agreed to cut several 4-in rings from the shell to send to ORNL for testing and welding evaluation.

August 11-12: Representatives of ORNL visited SI to conduct welding trials on additional 4-in rings cut from the first IC396M casting, and to train SI welders. Some difficulty was experienced making crack-free welds on the centrifugally cast roll shell, but the SI welders appeared capable of making the welds.

August 17-18: Representatives of ORNL and Metallamics visited SI to witness casting of the second IC396M roll shell. The quality of the second castings was comparable to that of the first. The schedule for final assembly of the rolls was discussed, and a target date of mid-October was proposed for delivery to Burns Harbor. It was agreed that ORNL would supply all of the welding wire for both the welding trials and final assembly requirements. SI expressed concerns that weld quality was too unpredictable and the weld process too slow for a production process. They suggested that mechanical pinning be considered as an option for attaching trunnions to roll shells, and it was agreed to incorporate pinning into the scope of work.

October 1993-September 1994

December 7: Difficulties with machining and production scheduling had delayed delivery of the IC396M rolls when ORNL staff visited SI to assist with their assembly and welding. In the interim it was decided to fabricate one roll with welded trunnions, and the other with mechanically pinned trunnions. Difficulties were encountered with the welding, but eventually, with the assistance of an ORNL welding specialist, the required welds were completed and they appeared to be of adequate quality. A bar of IC218LZr Ni₃Al alloy was provided by ORNL for machining of the pins for the second roll assembly. A shipping date of December 17 was anticipated.

January 24: Both IC396M transfer rolls were installed in the slab reheating furnace at the 160-in Plate Mill at Burns Harbor.

c. February 21: Routine inspection revealed that cracks developed in the welds of the roll made with welded trunnions. The rolls, however, appear to be functioning properly, and the IC396M alloy was performing as desired in the service conditions of the furnace.

May 9: Representatives of ORNL and Metallamics visited Burns Harbor to inspect the IC396M transfer rolls during a routine, scheduled shutdown. The welded roll assembly was removed at this time for reworking and later reinstallation. Overall performance of the IC396M alloy and weld metal alloy appeared excellent. Weld cracking was a continuing concern. However, Bethlehem Steel expressed interest in an expanded installation of Ni₃Al rolls. Options for repairing the removed roll were also discussed, and it was decided that, for the sake of expediency, this roll would be reworked for pinning and reinstalled at the earliest possible time.

Mid-July: The roll that was originally welded was machined for pinning and reassembled at SI during June. This welded/pinned roll was then returned to Burns Harbor and reinstalled.

August 29: A meeting with representatives of Metallamics and SI was held at ORNL to discuss the possibility of a greatly expanded installation of Ni₃Al rolls. A previous meeting at Burns Harbor on August 15, established that Bethlehem Steel was agreeable to this possibility. Various issues relative to manufacturing additional rolls were discussed. It was agreed that Metallamics and SI would conduct an engineering analysis of roll production to identify ways of making Ni₃Al rolls competitive in the marketplace. A variety of technical issues were also discussed including: the possibility of making trunnions from an alloy other than Ni₃Al, the possibility of reducing Ni₃Al roll wall thickness, the feasibility of using mechanical pinning in production, and alternative designs for attaching trunnions to roll shells.

October 1994-September 1995

October 6: A discussion about the possibility of an expanded installation of Ni₃Al rolls at Burns Harbor was held at Department of Energy headquarters. The meeting was attended by representatives of ORNL, Metallamics, SI, Bethlehem Steel, and the DOE. The meeting affirmed that there is an important need for this type of collaborative effort throughout the steel industry, and that Ni₃Al alloys have real potential to solve long-standing problems associated with transfer rolls in steel heat treating facilities.

November 7: A meeting with representatives of Metallamics was held at ORNL to discuss technical and economic issues relative to manufacturing Ni₃Al transfer rolls on a production basis. The topics covered included: a general project review, surface finish requirements for future rolls and how to produce/control surface finish, the possibility of using alternate alloys for trunnions to lower roll cost and relieve concerns about welding. The need for an engineering analysis of roll manufacturing was stressed, and Metallamics agreed to take a lead role in formulating it.

Late December: During a routine inspection, Bethlehem staff discovered that the roll that originally used mechanical pinning to attach its trunnions had failed. All six pins on one trunnion had sheared, and the roll was taken out of service. Intense discussions began on the cause of the failure, and whether this roll could be repaired and reinstalled.

March 10: A meeting at SI was held with representatives of ORNL and Metallamics to examine the pinned roll that was taken out of service and returned to SI. This roll was examined in detail, but there was no consensus about the exact cause of failure. During the January-March period an extensive stress analysis of the roll was done, including the effects of service loading, number and configuration of pins, and design and placement of welds.

May 10: Another discussion about repairing the pinned roll was held at SI with the same participants. Additional stress analysis results were discussed in detail. It was agreed that the failed roll would be repinned, and the main topic of discussion was the size, placement and number of pins required to prevent a reoccurrence of failure. It was decided to use threaded studs to effect the repair and to arrange the studs on two staggered rows of six each. SI would perform all necessary machining and return the roll to Burns Harbor for reinstallation.

June 5: A meeting was held at Burns Harbor to review analysis of the failed roll and to discuss plans for its repair and reinstallation. The meeting was attended by representatives of ORNL, Metallamics, and SI. Highlights of the roll stress analysis were presented, and the rationale for repinning the failed roll was described in detail. Bethlehem staff were quite pleased with plans to repin this roll, and agreed to reinstall the repaired roll at the earliest possible time. The heat treating furnace was shut down for inspection, and the welded/pinned roll that was still in service was examined. The pins on this roll appeared to be performing well, and the expectation was that the roll would continue to function properly.

July 3: The repaired pinned roll was reinstalled in the reheating furnace in the 160-in plate mill at Burns Harbor.

PROGRESS SUMMARY

The overall objectives of this cooperative project were to fabricate transfer rolls of a Ni₃Al alloy and to evaluate their performance under actual service conditions in an industrial heat treating facility. These

objectives were clearly met. Considerable analysis of the actual operating state of rolls was done using finite element analysis, and this information was used to design for both welded and mechanical attachment of trunnions to roll shells to form completed transfer roll assemblies. Procedures suitable for welding trunnions to roll shells were developed, and welders were trained to work with the Ni₃Al alloys. Procedures necessary for melting and analyzing the chemistry of Ni₃Al alloys under actual industrial melt shop conditions were established and implemented. Two high quality centrifugal castings of the IC396M alloys were produced for roll shells. Four high quality static castings of IC396M were produced for trunnions.

As of September 1, 1995, the roll that was originally welded, and then repaired by pinning has accumulated about 16 months of service time. The roll that was originally pinned, and then repaired by repinning has accumulated about 13 months of service time. Both rolls continue to function properly. They appear to be more resistant to scoring and to have much better dimensional stability than similar rolls made from conventional iron-based heat resistant alloys. The expectation of longer service life for Ni₃Al rolls, and their having a favorable impact on product quality appears reasonable. The end user, Bethlehem Steel Corporation is satisfied with the roll performance, and they are very interested in continued evaluation.

INVENTIONS

The work performed under this CRADA did not result in any new inventions.

SUMMARY OF INDUSTRIAL SUPPORT

Metallamics, Sandusky International, and Bethlehem Steel Corporation provided substantial in-kind contributions in the form of design, engineering, materials, project coordination, and use of production equipment.

Specifically, Metallamics identified the transfer roll application and potential end users, provided melt stock materials for the centrifugal castings, coordinated delivery of materials to foundries for melting and casting of trunnions and roll shells, and coordinated the scheduling of manufacturing and installation of the rolls. Sandusky International performed the chemical analyses, melting, casting, welding, and machining of the IC396M alloy necessary to manufacture the completed rolls. They also performed the repairs necessary to reinstall and continue evaluation of the rolls. Bethlehem Steel Corporation made their facilities at the 160-in plate mill in the Burns Harbor Plant available for evaluation of the Ni₃Al rolls under actual industrial conditions.

BENEFITS TO THE DEPARTMENT OF ENERGY

The mission of the Advanced Industrial Materials Program is to conduct applied research, development, and applications engineering work, in partnership with industry, to commercialize new or improved materials and materials processing methods that will improve energy efficiency, productivity, and competitiveness. This CRADA project supported the AIM Program mission by working with a materials supplier and end-user to identify a significant opportunity for improved efficiency and energy savings through the use of new materials (Ni₃Al alloys), and, by forming an industry/DOE National Laboratory team to solve the engineering problems attendant to industrial use of the Ni₃Al alloys. The work completed on the CRADA clearly established the technological benefits of using Ni₃Al alloys for the

transfer roll application. Furthermore, it indicates that with continued development, the anticipated result of improved energy efficiency and productivity will be realized.

PLANS FOR FUTURE WORK

The management of Bethlehem Steel's Burns Harbor Plant are very encouraged by the performance of the nickel aluminide rolls. They believe these rolls offer a viable solution to a chronic problem in their facility. Bethlehem Steel is continuing to evaluate the currently installed rolls, and they are interested in the possibility of installing additional rolls. Sandusky International views manufacturing nickel aluminide rolls as a significant opportunity to expand their business base. They are interested in producing additional rolls including optimizing the melting and casting process, and examining ways to reduce manufacturing costs. Based on the high level of interest of the key industrial participants, the development of Ni_3Al alloys for the transfer roll application will continue on a collaborative basis.

BUDGET SUMMARY

AIM Materials (B&R ED 22 04 00 0)

Budget: FY93 = \$75K FY94 = \$100K FY95 = \$50K Total = \$225K

Actual: Total = \$218,467 (as of 08/25/95)

ACKNOWLEDGEMENT

Completion of this project involved a significant level of effort from a relatively large group of participants.

From ORNL, the support, encouragement, and overall management provided by P. A. Angelini and P. S. Sklad are gratefully acknowledged. V. K. Sikka provided overall coordination of the technical aspects of the project, especially communications with industrial participants. J. D. McNabb and D. W. Swaney provided considerable support for welding activities. R. W. Swindeman provided assistance on mechanical behavior issues and general support on engineering activities. G. A. Aramayo and J. V. Platt conducted mechanical engineering analyses related to design and operation of the rolls.

From Sandusky International, C. W. Rainger and D. A. Scott provided overall management and coordination of activities at their foundry. W. H. Bade and L. E. Gardner were responsible for coordinating melting and casting. S. P. Hawk provided support for engineering activities. R. D. Gearheart coordinated machining and welding activities. E. G. Kay and J. C. Rogers provided support of all metallurgical and engineering activities.

From Bethlehem Steel Corporation, A. W. Simola and D. W. Elwood agreed to the ultimate installation of the Ni_3Al transfer rolls in the plate mill they manage at the Burns Harbor Plant, and they provided the support and coordination necessary to conduct the desired evaluation.

INTERNAL DISTRIBUTION

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