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CONF-940367--3

CERTAIN ASPECTS OF THE MELTING, CASTING AND WELDING OF Ni_3Al ALLOYS*

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ABSTRACT

The development of effective processing and fabrication technologies is crucial to the commercialization of Ni_3Al alloys. Two alloys under development for castings are known as IC221M, with a nominal composition of Ni-8Al-7.7Cr-1.4Mo-1.7Zr wt%, and IC396M, with a nominal composition of Ni-8Al-7.7Cr-3Mo-0.85Zr wt%. These alloys can be melted and cast using the techniques normally used for Ni-based materials. Oxidation of the liquid alloys is a concern, but it can be controlled by the use of vacuum processing or the judicious use of inert gas cover during processing. The liquid alloys can react with silica and zircon sands during casting, but this can be controlled through the use of appropriate mold washes like carbon-based materials. Welding studies showed that these alloys are susceptible to solidification cracking in weld fusion zones. The cracks are generally associated with the occurrence of the Ni-Ni_5Zr eutectic in interdendritic regions of the weld microstructure. The amount of eutectic in the weld microstructures increases with Zr concentration in the weld filler metal. Weld filler metal Zr concentrations of 3 wt% and higher were found effective for preventing solidification cracking of weld deposits on the base casting alloys. The solidification cracking behavior is consistent with the accepted phenomonological theory of this process. A weld filler metal with a composition of Ni-8Al-7.7Cr-1.5Mo-3.0Zr wt% was prepared, and used to gas tungsten arc weld together 15-mm-thick plates of the IC221M alloy. This weldment was free of cracks. Weldment tensile specimens were machined from the plate and tested at 21, 800, and 900 °C. The weldment yield strength at the elevated temperatures was higher than that at room temperature, and it was nearly comparable with that of the base IC221M alloy. The status of the evaluation of the cast Ni_3Al alloys for furnace furniture, turbocharger rotors, and manufacturing tooling is also briefly discussed.

This work was sponsored by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Industrial Technologies, Advanced Industrial Materials (AIM) Program, under contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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INTRODUCTION

Traditionally, intermetallic compounds were viewed as prototypic brittle materials. Work over the last decade, however, has demonstrated that the ductility and engineering properties of certain intermetallic compounds, like Ni_3Al, can be substantially improved through the application of alloy development principles to these systems. (Ref. 1,2) Depending on composition and processing, tensile elongations near 50% are reported for Ni_3Al alloys. Other desirable properties ascribed to Ni_3Al 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, Ni_3Al 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 are for Ni_3Al alloy castings. This paper will briefly review the characteristics of the cast Ni_3Al alloys giving special emphasis to welding development work. Several applications for which these alloys are being evaluated will also be mentioned.

ALLOY CHARACTERISTICS

Nominal compositions of the two Ni_3Al 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. (Ref. 3) 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.

A microstructure from an IC221M casting is shown in Fig. 1, and it typifies the microstructure found in both alloys. The matrix in IC221M and IC396M is the ordered $L1_2$ phase Ni_3Al (commonly referred to as γ'). In addition, these alloys typically contain about 5-10 volume % of the disordered γ phase which appears as the lacey network in Fig. 1. Depending on composition and the cooling conditions, these cast alloys can also contain up to about 5 volume % of the eutectic, Ni-Ni_5Zr, which is marked by arrows in Fig. 1. While the eutectic constituent is largely responsible for improving the casting characteristics of the alloys, it melts near 1170°C, and thus, limits their hot working temperature. Both alloys can be cold worked with intermediate annealing at 1100°C.

Table 1. Nominal compositions of cast Ni_3Al 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

MELTING AND CASTING CONSIDERATIONS

Important factors that require special attention in the melting of Ni_3Al alloys include: the exothermic nature of the intermetallic compound formation reaction; and, the general reactivity of the elements involved in forming these alloys. The extent of exothermic reaction in the Al-Ni binary system is substantial (Ref. 4), and the proper use of the exotherm during melting can result in savings of both the energy and the time needed for melting. One way of realizing a benefit from the exothermic reaction is by carefully controlling the loading sequence of metal in melting furnaces as illustrated in Fig. 2. Using this arrangement, Al is the first metal to melt. It then reacts exothermically with Ni to form an NiAl liquid with a temperature exceeding 1640°C, which then flows down rapidly melting the charge materials below. Within a very short time the entire bath becomes molten. This scheme has been used successfully to melt 2500 kg heats of Ni_3Al alloys. (Ref. 5)

Air melting is the simplest and least expensive process for melting Ni_3Al alloys, and for many applications, it is more than adequate. The high Al levels in these alloys promote the rapid formation of continuous Al_2O_3 films on the tops of melts. Once it forms, the oxide film is believed to be relatively protective of melts, and an important factor in controlling Al recovery and maintaining low levels (< 40 ppm) of the oxygen and nitrogen usually found in air-melted heats. (Ref. 6) The Al_2O_3 film also contributes to the high recovery of other alloying elements. (Ref. 7) Although air melting meets the recovery requirements for Ni_3Al alloys, it is nonetheless recommended that melting be done under argon cover if possible. One reason for this is that the protective Al_2O_3 film may frequently be disturbed during commercial melting, for instance, for chemical analysis sampling. Each time the oxide film is disturbed, fresh molten metal is exposed to air, and recovery of alloying elements will be affected. The Ni_3Al alloys can be melted by a variety of other techniques including vacuum induction melting, vacuum arc remelting, and electroslag remelting. (Ref. 6,7)

The major concern in the casting of Ni_3Al is their relatively high chemical reactivity. Exposure to air causes rapid formation of Al_2O_3 skins and this can be a problem if transferring molten metal to ladles or pouring in air. The effects of exposure to air can be minimized by flooding ladles and mold cavities with argon, using bottom pouring techniques or by casting in vacuum. The reaction of Ni_3Al melts with mold materials is also an important consideration. For example, Zr in these alloys can react with silica and zircon based sands and washes to form ZrO_2 inclusions in the surface of castings. The ZrO_2 inclusions act as crack initiators during cyclic loading and reduce fatigue life. Carbon based molds and washes can completely eliminate this problem. (Ref. 8)

WELDING DEVELOPMENTS

Background

The welding process induces thermal stresses in a material. These thermal stresses are due to the thermal expansion and contraction associated with local heating, plastic yielding, cooling, and melting. (Ref. 9,10) Thermal stresses also can be augmented by other factors such as the geometry of parts or the presence of residual stresses in a part caused by casting, forming, or other types of processing. If a material is to be welded, and if it is desired that the welds have a high probability of being free of cracks, then that material must have a microstructure that is resistant to the action of the induced thermal stresses.

Alloys which are unable to accommodate the thermal stresses produced by welding commonly experience cracking in either the base material or the weld fusion zone or both. Cracking which originates in the base material near a weld fusion zone is known as heat-affected zone (HAZ) cracking. Numerous studies (Ref. 11-13) have related HAZ cracking to important alloy properties such as low strength and ductility at high temperatures (> 1000°C), low thermal conductivity, and liquation of second phase particles in the base material. Cracking which originates in weld fusion zones is generally of the type known as solidification (or hot) cracking, and it is caused by the quantity and distribution of liquid around grain boundaries during freezing of the weld through a critical solidification range. (Ref. 12,14) Because of their strong dependence on the mechanical, physical and thermodynamic properties, both types of cracking are primarily related to alloy composition.

Although significant progress has been made in the efforts to commercialize Ni_3Al alloys, important technological issues related to the processing, fabrication, mechanical behavior, and environmental resistance of these alloys still require further study and analysis. Weldability, i.e., whether defect-free welds can be made in a material, is a specific issue related to fabrication and repair of cast Ni_3Al alloys that are presently under study. Alloys which have good weldability generally will have much more commercial appeal, and therefore greater opportunity for widespread use, than those which cannot be welded.

The cast Ni_3Al alloys IC221M and IC396M have relatively low resistance to solidification cracking, and therefore, they are susceptible to weld cracking. Crack-free welds can be made on the alloys only with difficulty, and with poor reproducibility. Based on metallographic analysis of solidification cracks in welds of IC221M, modest composition modifications were made to the base alloy to improve solidification-cracking resistance. The tensile properties and processing characteristics of the modified alloy, called IC221W to denote improved weldability, were evaluated and found to be comparable to those of the base alloy, IC221M. Also, a welding filler metal was fabricated from the IC221W alloy and used to weld plates of cast IC221M. A crack-free weldment was obtained, which had good tensile properties up to 900°C.

Experimental

The nominal compositions of the alloys used for the welding development work are shown in Table 2. The alloys were made from pure charge materials. Chemical analysis of selected heats showed little deviation from target compositions, and that contamination by undesirable trace elements (e.g., C, N, O, P, S) was minimal. Ingots of the IC221M and IC221W alloys were made by two techniques: 25 x 25 x 75 mm cast bars were made by vacuum arc melting and drop casting into copper molds; and, 68-mm-diameter x 90 mm cast bars were made by vacuum induction melting and casting into copper molds. Only cast 25 x 25 x 75 mm bars were made for alloy 14540.

Table 2. Nominal compositions of experimental Ni_3Al alloy castings used for welding studies, in wt %.

I.D.	Concentration, wt%				
	Ni	Al	Cr	Mo	Zr
14540	82.8	8.0	7.7	1.5	0.0
IC221M	81.3	8.0	7.7	1.5	1.5
IC221W	79.8	8.0	7.7	1.5	3.0
14994	78.3	8.0	7.7	1.5	4.5
14995	76.8	8.0	7.7	1.5	6.0

The 25 x 25 x 75 mm bars were used for evaluation of both welding and processing behavior. Both automatic and manual gas tungsten arc (GTA) welds were made on the castings. The types of GTA welds made were: autogenous bead-on-plate (BOP) welds, autogenous groove (AG) welds, and groove welds with welding filler metals of the same compositions as the castings. The autogenous GTA welds were made automatically under closely controlled conditions using argon gas shielding and no preheating. The groove welds made with filler metal were made manually with Ar gas shielding and no preheating. Only autogenous BOP welds were made on alloys 14540, 14994 and 14995.

Filler metals for the manual GTA groove welds were prepared by cutting 25 x 25 x 6 mm coupons from the smaller bar castings, and cold rolling these into 1-mm-thick sheets using successive 10% reductions followed by annealings at 1100°C in vacuum. These sheets were then cold sheared into 1-2-mm-wide strips which were used for weld filler metals. The bar castings were prepared for the manual GTA welds by cutting a 6.4-mm-deep x 50-mm-long groove into the 25 x 75 mm faces. The grooves had root radii of 3.2 mm with included angles of 80°.

The larger castings were used to measure solidification cracking susceptibility, and for evaluation of the tensile properties of both IC221M and IC221W. Measurement of solidification cracking susceptibility was done using the SigmaJig test. (Ref. 15) Specimens for this test were prepared by machining 0.76-mm-thick disks from the 68-mm-diameter castings, then cutting them into plates about 50 mm square. Also, eight 12.7-mm-diameter x 82.6-mm-long bars were cut from each of these castings and machined into tensile specimens with gage diameters of 6.35 mm and gage lengths of 31.75 mm. The tensile specimens were tested in air at temperatures up to 1050°C. Also, 15-mm-thick plates were cut from an IC221M ingot and welded together with IC221W filler metal using the GTA process. Tensile specimens were prepared from this plate transverse to the welding direction. The weldment tensile specimens had gage diameters of 3.18 mm and gage lengths of 47.5 mm. These specimens were tested in tension in air at temperatures up to 900°C. All of the tensile tests were done at a crosshead speed of 5.08 mm/min, and the specimens were equilibrated for 30 min at each temperature before testing.

Welds were inspected visually and optically at low magnification (up to 30X) for evidence of cracking. The welded IC221M plates were radiographed using standard techniques. Selected specimens were also examined metallographically, both optically and in a scanning electron microscope (SEM). Volume fractions of various phases were determined by standard metallographic techniques. Standardless, semiquantitative microchemical analyses were done in the SEM using an energy-dispersive x-ray spectrometer (EDS) system.

Results and Discussion

Solidification Cracking in IC221M welds - The cross sectional view of a single-pass manual GTA weld made in an autogenous grooved IC221M casting, Fig. 3, typifies the cracking usually observed in welds of this alloy. The large crack at the weld centerline extended for nearly the entire length of the weld bead, about 50 mm. The smaller cracks near the edges of the weld bead which did not extend to the weld surface are also often observed. The cause of the weld cracking in this alloy was determined by examining the interior crack surfaces, and by examining the phases associated with the cracks on polished sections. The appearance of a weld crack surface is shown in Fig. 4. The irregular features on this surface correspond to the solidification substructure, and the smoothedover appearance is characteristic of a crack which formed in the presence of liquid, i.e., a solidification crack.

The microstructure in the vicinity of a crack, as found on an unetched polished section, is shown in Fig. 5(a). Two microstructural features were associated with the solidification cracks: a lamellar microconstituent is clearly evident, and is separated from the matrix by a visually distinct transition layer, Fig. 5(b). Using area scans, the overall composition of the lamellar microconstituent was determined to be: 74.4 Ni-4.2 Al-7.7 Cr-3.0 Mo-10.7 Zr wt%. The compositions of the individual lamella were: 70.9Ni-1.4 Al-2.8 Cr-1.6 Mo-23.3 Zr wt%; and 78.6 Ni-6.1 Al-10.7 Cr-3.2 Mo-1.4Zr wt%, respectively. The microchemical data indicate that there is a strong redistribution of Mo and Zr to interdendritic regions during the solidification of this alloy. The appearance and overall composition of the lamellar microconstituent indicate that it is a variation of the Ni solid solution-Ni_5Zr eutectic found in the Ni-Zr binary system at the composition of Ni-13 Zr wt% and the eutectic temperature of 1170°C. (Ref. 16) The compositions of the individual lamella are also consistent with this conclusion. The thin transition zone adjacent to the crack surface between the eutectic and the matrix had a composition of 83.8 Ni-7.6 Al-5.3 Cr-1.4 Mo-1.9 Zr wt%. The lower alloy content of this phase compared to others in this region indicates that it may have formed as a proeutectic phase during solidification of the interdendritic liquid.

Welding of cast Ni_3Al alloys - The susceptibility to solidification cracking in welds and castings is related to the amount of liquid phase present when the solidus temperature is reached. (Ref. 12) In binary eutectic systems, there is a critical range between the limit of solid solubility and the eutectic composition where the susceptibility to solidification cracking is maximized. At compositions outside of this critical range, either lower in solute or nearer to the eutectic composition, solidification cracking is much less likely to occur. Based on this theory, and the fact that a Ni-Zr eutectic was associated with solidification cracking in the IC221M welds, it was decided to investigate the importance of Zr concentration in the alloy to solidification cracking. Four additional alloys were melted and evaluated: alloy no. 14540, containing no intentional Zr addition, IC221W containing twice the nominal Zr concentration as IC221M, and alloys no. 14994 and 14995 containing even high Zr concentrations.

Autogenous BOP welds in alloy no. 14540 showed extensive cracking along grain boundaries in the fusion zone, and no further evaluation of this alloy was done. Similar autogenous BOP welds on IC221M and the high-Zr alloys were crack-free. Optical metallography showed that 14540 contained none of the Ni_5Zr eutectic. In comparison, microstructures of the welds in the alloys containing Zr were similar except that the volume fraction of the interdendritically distributed eutectic increased with the Zr concentration of the alloy as shown in Fig. 6.

Autogenous welds on the IC221M and IC221W alloys were then made in grooves to increase the restraint conditions. Under this condition, only IC221W remained crack-free. Also, a weld bead made with a matching filler metal addition in the grooved IC221W casting was free of cracks. Two additional GTA weld beads were made in this groove, shown in Fig. 7, and each was acceptable.

These results indicated that Zr concentration was an important factor in determining whether solidification cracking occurred in welds of alloys based on the IC221 composition. SigmaJig testing was done to gain a little more insight into this behavior. SigmaJig testing is done by variably restraining a thin-plate or sheet specimen of an alloy by applying a stress transverse to the welding direction prior to welding. (Ref. 15) Using a standardized set of welding parameters, an autogenous weld is produced along the specimen centerline. By varying the magnitude of preapplied stress and observing whether cracks occur, a unique threshold stress value can be established, above which cracking always occurs for a given material and a given set of welding parameters. This threshold stress is extremely reproducible and can thus be used as a quantitative measure of resistance to solidification cracking during welding. Results from initial SigmaJig testing of IC221M and the high-Zr alloys are shown in Fig. 8. These data show that for a Zr concentration of 1.5 wt% the threshold stress is zero, meaning that alloys of the IC221M composition are highly susceptible to solidification cracking. Alloys with Zr concentrations above 1.5 wt% all had measureable threshold stresses, with the highest value obtained for the alloy containing 4.5 wt% Zr.

These welding and SigmaJig testing results are consistent with the phenomenological theory of solidification cracking (Ref. 14) to the extent that they show the susceptibility of these Ni_3Al alloys to weld solidification cracking was improved by increasing their Zr concentration, and thus the amount of eutectic in their microstructures. On the other hand, eliminating the Zr completely did not eliminate solidification cracking as theory would suggest. (Ref. 14) This result indicates that factors other than the amount of eutectic in the weld microstructure play a role in the solidification cracking behavior of the Ni_3Al alloys. For example, the solidification cracking theory does not account for the effects of alloy mechanical properties on cracking.

Tensile properties - To be of practical value, the alloy with increased Zr concentration, IC221W, should also have mechanical properties comparable to those of IC221M. The yield strength and reduction of area behavior of IC221M and IC221W are plotted with test temperature in Figs. 9(a) and 9(b), respectively. The yield strength of IC221W was slightly lower than that of IC221M at room temperature, 579 MPa compared to 620 MPa, but was virtually identical at elevated temperatures up to 1050°C. Both alloys showed an increase in yield strength up to 800°C, reaching values of 720 MPa, after which their yield strengths fell with continued increases in test temperature. Also, the effect of test temperature on tensile ductility was similar for both alloys as shown in Fig. 9(b). However, actual ductility values for IC221W were somewhat lower than those of IC221M, especially below about 800°C. The difference in ductility behavior may be due to a higher volume fraction of interdendritic phases in the IC221W alloy.

The 15-mm-thick plates of IC221M casting were welded together using a multiple bead procedure and filler metal of the IC221W composition. The plate edges were prepared with a double-vee bevel. The root pass was manually ground on its back side prior to completing the weld, which took eight beads deposited manually by the GTA process. Radiography showed that the weldment contained some porosity and lack-of-fusion defects, but was free of cracks. The weldment yielded 5 tensile specimens which were oriented transverse to the welding direction, with the weld centrally located in their gage lengths. Tensile data from these specimens are given in Table 3. The weldment specimens had very good tensile properties, and showed the increase of yield strength with test temperature which is characteristic of the base metal alloys. All of the specimens failed at least partially in the weld. Examination of the specimens tested at room temperature indicated that the specimen with lower tensile strength and ductility contained a large weld porosity defect in the plane of fracture. Only the specimen tested at 900°C fractured entirely within the weld.

Table 3. Tensile Data from IC221 Weldment

Test Temperature °C	Yield Strength MPa	Tensile Strength MPa	Total Elongation %	Reduction of Area %
21	538.3	601.2	3.43	1.12
21	532.1	793.3	11.71	2.25
800	692.1	816.9	2.40	0.20
800	736.3	818.4	3.78	1.92
900	593.6	637.9	1.87	3.25

Based on these test data, it can be concluded that the tensile properties of IC221W are nearly comparable to those of IC221M, and that acceptable levels of strength and ductility can be developed in welds of IC221M made with IC221W filler metal.

STATUS OF APPLICATIONS

While the cast Ni_3Al alloys are still under development, they appear to have potential for use in several important applications. Several areas where additional processing development, testing, and service evaluation are being actively pursued are outlined in the following paragraphs. The ability to successfully weld the cast Ni_3Al alloys is an important element of these commercialization efforts because of the needs to weld repair castings for cosmetic and structural purposes, and to fabricate components from cast parts.

Furnace furniture

Both IC221M and IC396M are being evaluated for a variety of furnace furniture applications which take advantage of the oxidation and carburization resistance, and favorable high temperature mechanical behavior and wear properties of these alloys. The type of parts being evaluated include support trays and posts, walking beams, and transfer rolls. These components are being made by static sand casting techniques at several foundries including Alloy Engineering & Casting Company (Champaign, IL), and by centrifugal casting at Sandusky International (Sandusky, OH). A ring cut from centrifugally cast pipe of IC396M having a nominal diameter of 355 mm is shown in Fig. 10. This specimen was used for an evaluation of the turning, grinding and drilling characteristics, which are similar to those of other high strength Ni-based alloys. The Ni_3Al alloys are believed to have excellent potential to provide better performance than Fe-based heat resistant alloys in certain furnace furniture applications, and welding is playing a critical role in their success.

Turbochargers for diesel engines

Cast Ni_3Al alloys are being intensively evaluated as replacements for the Ni-based superalloy IN713LC which is commonly used as a turbocharger rotor material in diesel engines. The major benefits of the Ni_3Al alloys are improved fatigue life and the potential for lower material costs. The rotors are manufactured by investment casting at Precision Castparts Corporation (Portland, OR) and are being tested by Cummins Engine Company (Columbus, IN).

Manufacturing tooling

The Ni_3Al alloys also have potential for use in a variety of materials processing situations including dies for elevated temperature forging and hot pressing, and permanent molds for metal casting and glass forming. The tooling applications best suited to take advantage of the properties of the Ni_3Al alloys are those where processing occurs in the temperature range of 700-1000°C. Because of their oxidation resistance, elevated temperature strength and chemical compatibility, the cast Ni_3Al alloys were chosen as the die material for the hot pressing of Fe-B-Nd magnetic powders for automotive applications. Metallamics, Inc., (Traverse City, MI) is responsible for this development.

SUMMARY AND CONCLUSIONS

Some special considerations are necessary for the melting and casting of Ni_3Al alloys because of the exothermic nature of Ni-Al reactions and the chemical reactivity of Al and other alloying elements in these materials. When the necessary precautions are taken, Ni_3Al alloys can be melted and cast with relative ease. Films of Al_2O_3 can form on the tops of melts and during casting. These films can contribute to good recovery of alloying elements, but are undesirable during the casting process. Oxidation of liquid Ni_3Al alloys can be controlled by vacuum processing or by providing good argon cover during melting and pouring operations.

The following conclusions can be made based on the welding development studies:

1. The Ni_3Al alloys IC221M and IC396M are susceptible to solidification cracking in weld fusion zones. Solidification cracks in these alloys are associated with a Ni-Ni_5Zr eutectic which occurs at a temperature of about 1170°C.

2. Welding trials on alloys based on the IC221 composition showed that removing Zr did not improve solidification cracking, but that increasing the Zr concentration did. Weldability testing using the SigmaJig technique indicated that the optimum Zr concentration for controlling solidification cracking was in the range of 3-6 wt%. The welding results and weldability testing are consistent with the phenomonological theory of solidification cracking.

3. A welding filler metal was produced from an alloy designated IC221W containing a Zr concentration of 3 wt%, and it was used to GTA weld plates of cast IC221M. The weld was free of cracks. Weldment tensile test specimens showed the increase of yield strength that is characteristic of the cast Ni_3Al alloys like IC221M. The weldment tensile properties were nearly comparable to those of IC221M.

With considerable industrial cooperation, the cast Ni_3Al alloys IC221M and IC396M are being intensively evaluated for several important applications including furnace furniture, turbocharger rotors for diesel engines, and tooling for elevated temperature manufacturing processes.

ACKNOWLEDGMENT

Discussion of this work with and review of the manuscript by R. W. Swindeman and Srinath Viswanathan were appreciated. This work was sponsored by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Industrial Technologies, Advanced Industrial Concepts (AIC) Materials Program, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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Fig. 1. Typical microstructure of cast Ni_3Al alloys IC221M.

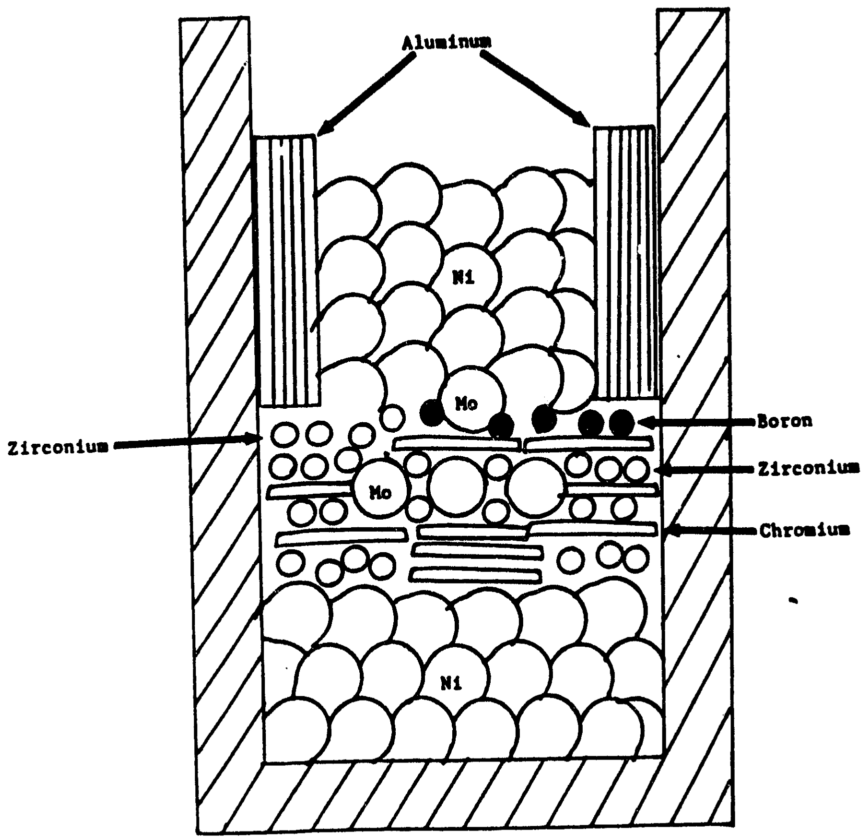


Fig. 2. Furnace loading sequence that takes advantage of the heat of Ni-Al alloys formation during the melting of Ni_3Al alloys.

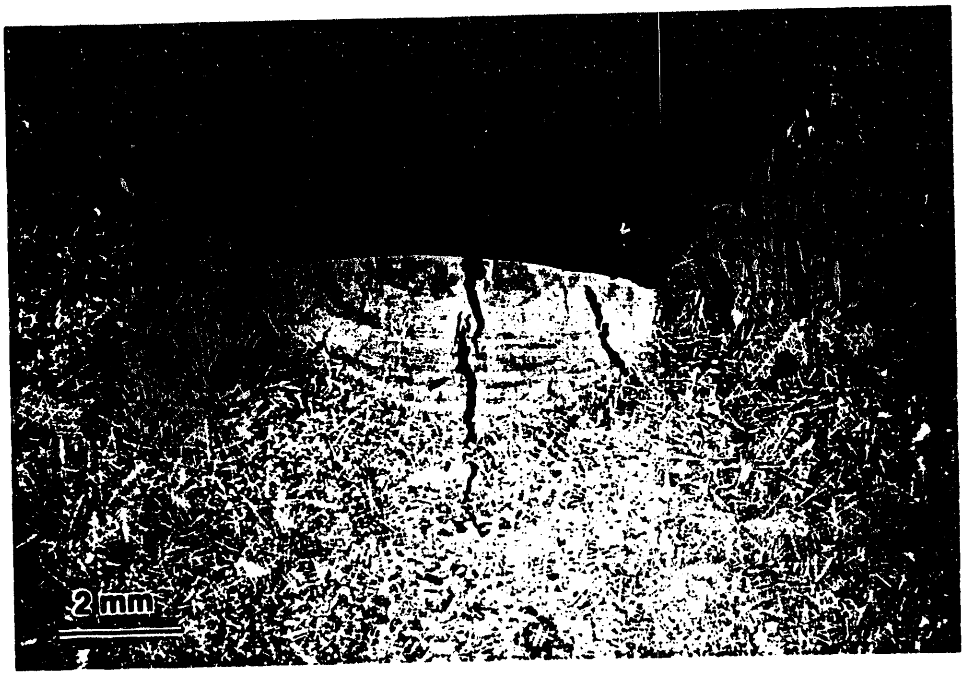


Fig. 3. Cross sectional view of a single GTA weld bead in a grooved IC221M casting made with IC221M filler metal.

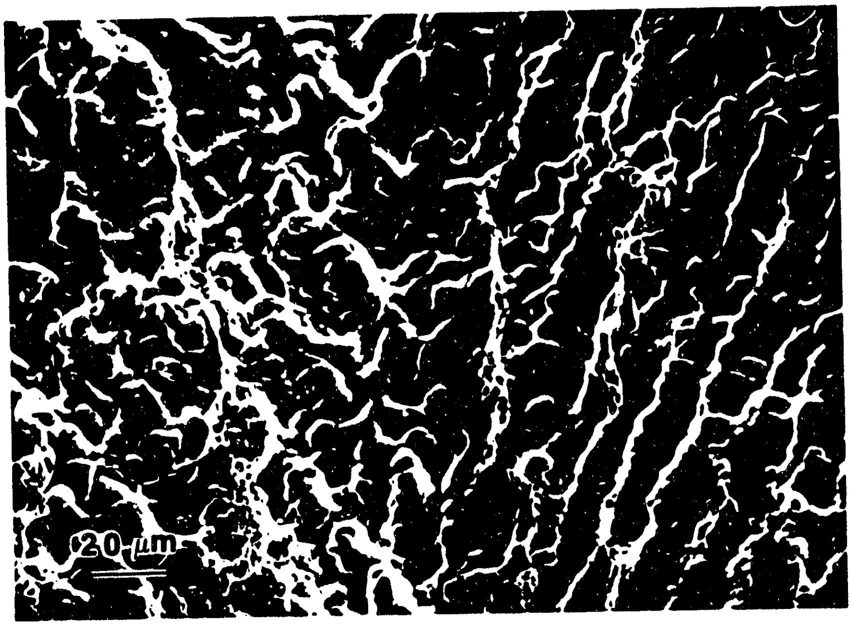
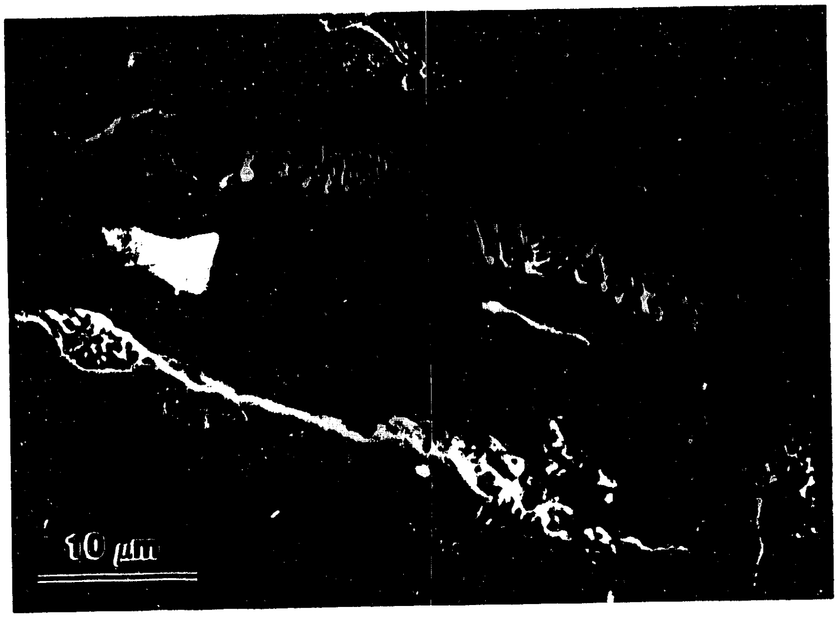


Fig. 4. SEM micrograph of weld crack surface. Appearance indicates liquid was present during crack formation confirming that this is a solidification crack.

(a)



(b)

Fig. 5(a). SEM micrograph showing microstructure near a solidification crack on an unetched, polished surface. Fig. 5(b). SEM micrograph showing detail of eutectic constituent at crack surfaces.

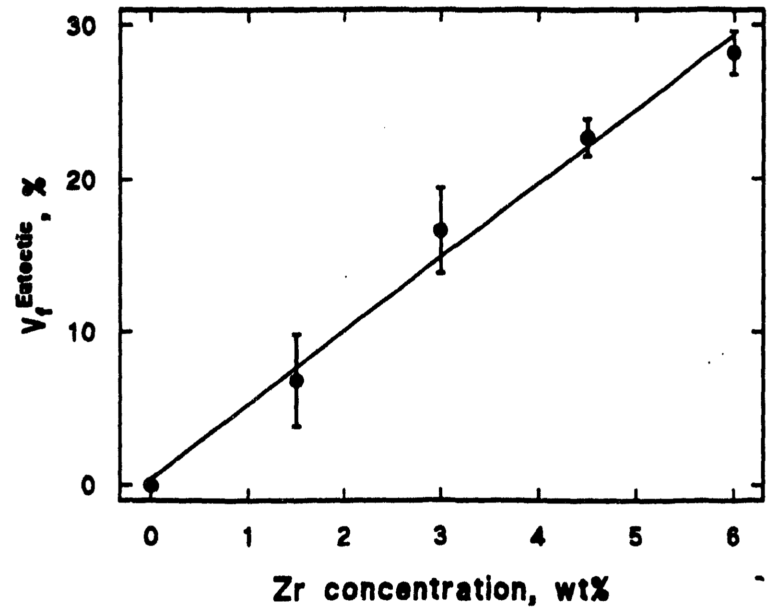


Fig. 6. Variation of amount of Ni-Ni_5Zr eutectic, expressed as volume %, with Zr concentration of alloys based on the IC221 composition.

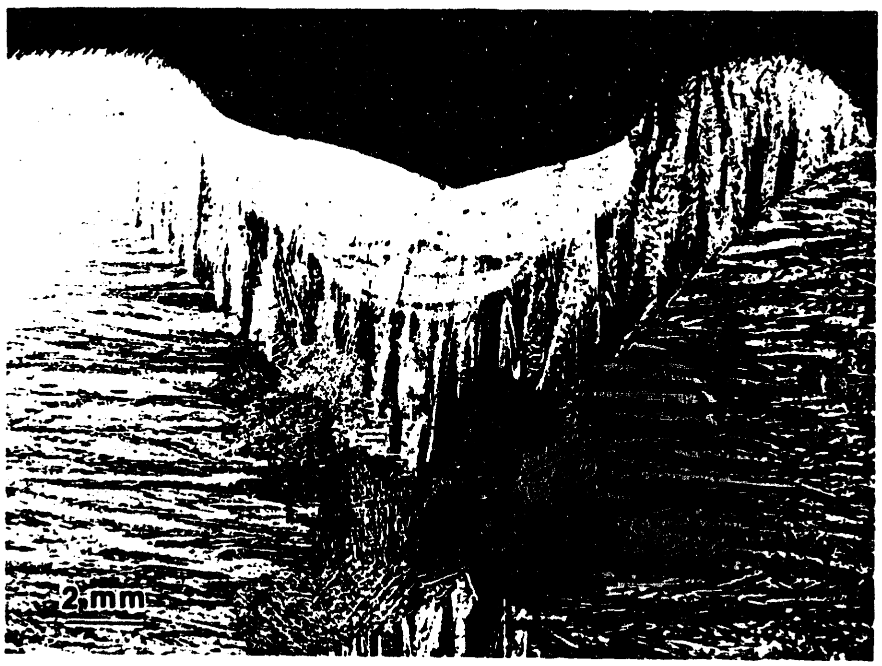


Fig. 7. Cross sectional view of GTA weld made in a grooved IC221W casting with IC221W filler metal. Weld contains three individual beads.

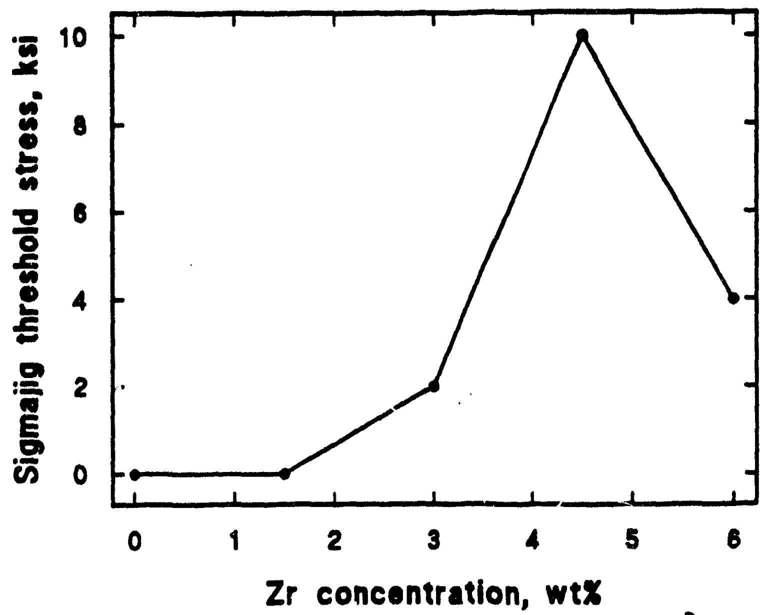


Fig. 8. Variation of threshold stress for solidification cracking with Zr concentration for alloys based on the IC221 composition.

(a)

(b)

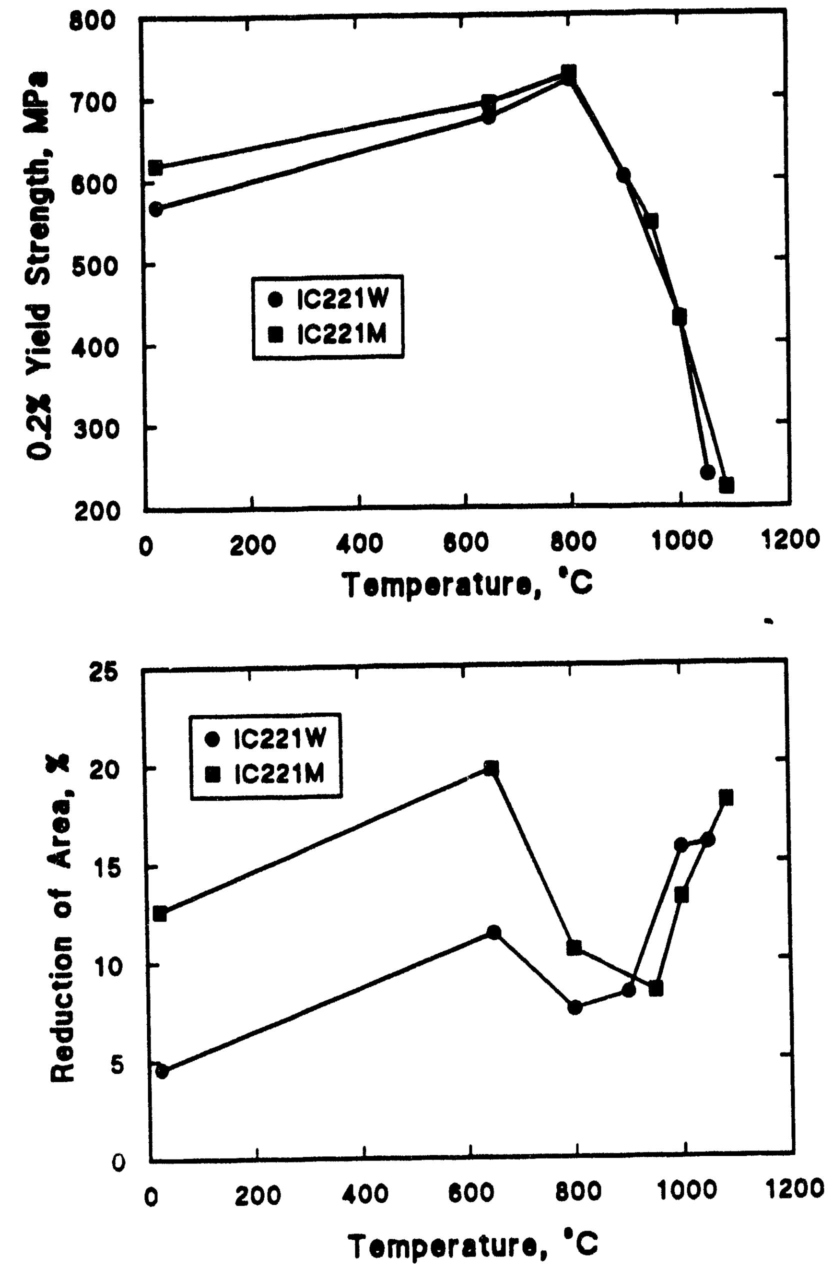


Fig. 9. Temperature dependence of the yield strength, (a), and the reduction of area, (b), from tensile testing of cast IC221M and IC221W.

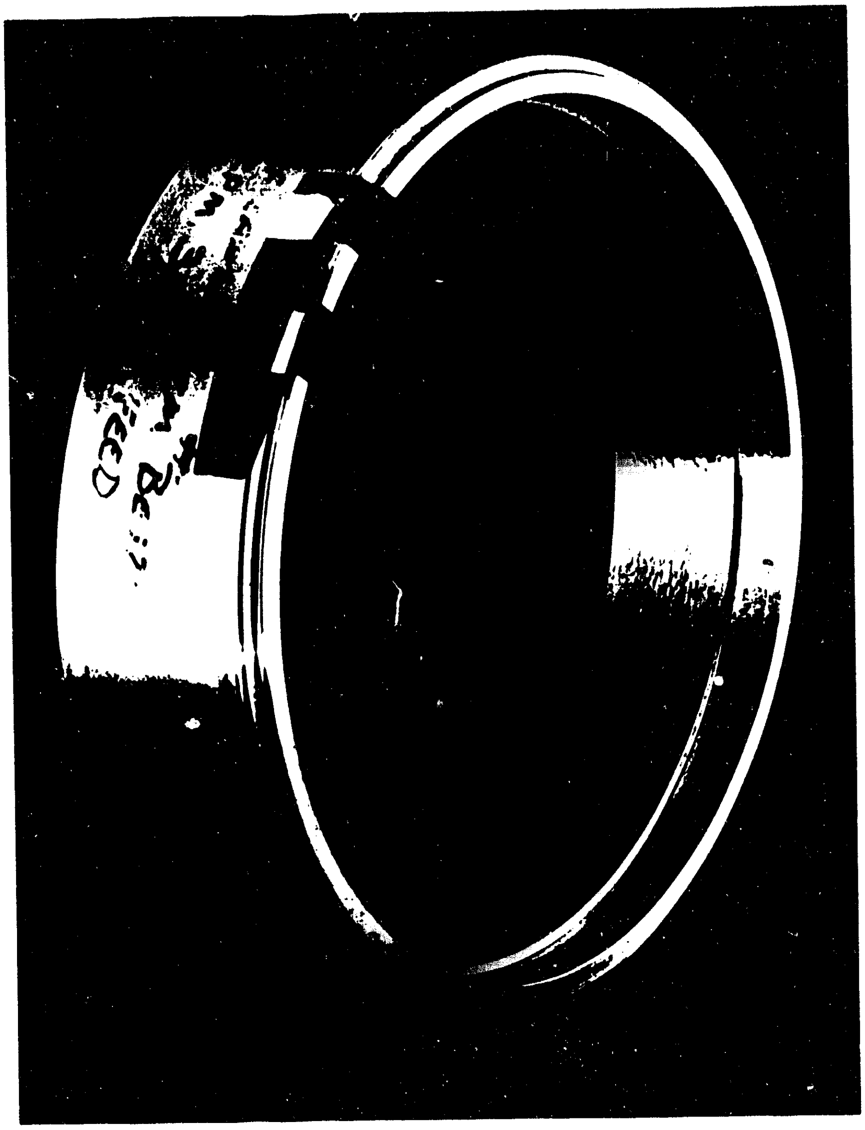


Fig. 10. Ring cut from 355-mm-diameter centrifugally cast pipe of IC396M and used for machinability testing.

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