UNIVERSITY OF CENTRAL FLORIDA
FROM PROMISE TO PROMINENCE
CELEBRATING 40 YEARS

AMPAC
"Bridging the technology gap"

Ternary Interdiffusion Coefficients in $Ni_3Al(L1_2)$ with Ir, Ta and Re Alloying Additions

N. Garimella[1], M.Ikeda[2], M.Ode[3], H.Murakami[3], Y.H. Sohn[1]

[1]Advanced Materials Processing and Analysis Center and
Mechanical, Materials and Aerospace Engineering
University of Central Florida, Orlando, FL, USA.

[2]Kobe Steel Co. Ltd., Japan.
[3]National Institute of Materials Science, Tsukuba, Japan.

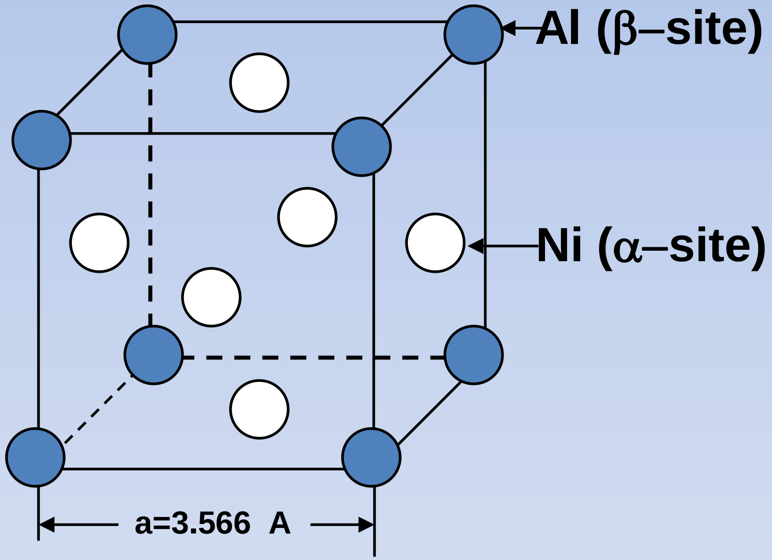
Objectives

- Determination of interdiffusion coefficients using selected ternary Ni_3Al with Ir, Ta or Re alloying additions:
  - ✓ $L1_2$ γ'-phase with approximately 25 at.% Al.
  - ✓ Solid-to-solid diffusion couples annealed at 1200°C for 5 hours.

- Assess the influence of Ir, Ta or Re on the interdiffusion behavior of Ni and Al at 1200°C :
  - ✓ Ternary interdiffusion coefficients - Boltzmann-Matano Analysis
  - ✓ Average ternary interdiffusion coefficients
  - ✓ Diffusional interactions and site preference

$L1_2$-γ′-Ni_3Al Lattice

- **Unique intermetallic phase coherently precipitates in fcc γ-phase of the Ni-base superalloys. This coherency is maintained by tetragonal distortion.**



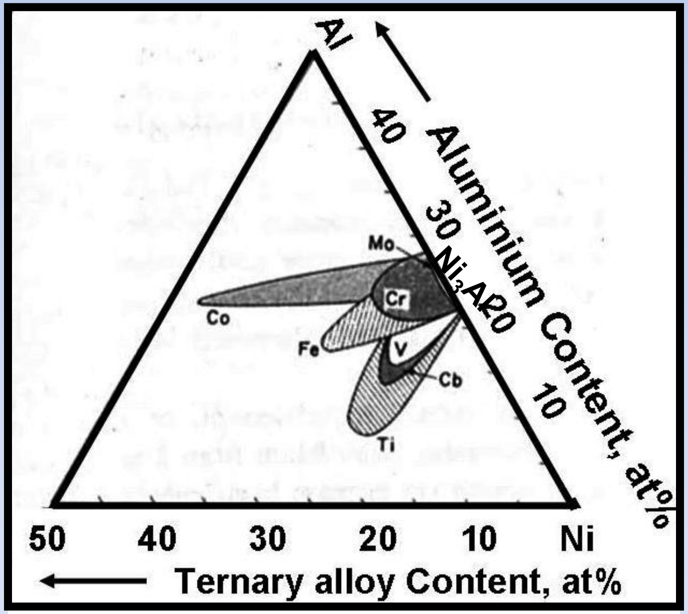
- **Microstructurally exists as a spherical or cube precipitates in superalloys, depending on the lattice mismatch.***

**R.F.Decker "Strengthening mechanisms in Nickel-base superalloys"*

$L1_2$-γ'-Ni_3Al Lattice and Alloying Constituents

- **Excellent mechanical strength and oxidation resistance. Ni-base superalloys find applications in Aviation/Land-based gas turbines.**

- **Relatively high electronegative elements (Fe, Ni and Co) compose α sites, where as high electropositive elements (Al, Ti, Ta or Nb) compose β sites of A_3B^*.**



Ni_3Al at 1100 C for various alloys**

- **α-site occupiers:**
  - ✓ **Ni, Pd, Pt.**
- **β-site occupiers:**
  - ✓ **Al, Ti, V, Cr, Zr, Nb, Mo, Hf, Ta, Re, Os and W**
- **α or β-sites occupiers:**
  - ✓ **Mn, Fe, Co, Cu, Ag and Au**

**R.F.Decker "Strengthening mechanisms in Nickel-base superalloys"*

*** Chao Jiang and B.Gleeson "Site preference of transition metal elements in Ni_3Al"*

**** Y.Minamino, H.Yoshida, S.B.Jung, K.Hirao and T. Yamane "Diffusion of Platinum and Molybdenum in Ni and N^{i}3Al"*

Alloying Constituents

Element	Atomic Radius	Crystal Structure	T_m (C)	Electron Configuration	Significance
Ni	1.24 A	FCC (3.52 A)	1455	$[Ar]3d^8 4s^2$	Strength and corrosion resistance through austenitic matrix and $L1_2$ precipitate.
Al	1.43 A	FCC (4.05 A)	660	$[Ne]3s^2 3p^1$	Strength through $L1_2$ precipitate.
Ir	1.36 A	FCC (3.84 A)	2410	$[Xe]4f^{14}5d^7 6s^2$	High strength alloys at high temperatures (upto 1200 C) than Ni-base superalloys . Excellent corrosion resistance. Complete miscibility Ni-Ir.
Ta	1.43 A	BCC (3.30 A)	2996	$[Xe]4f^{14}5d^3 6s^2$	High temperature strength. Corrosion resistance.
Re	1.38 A	HCP (a=2.76 A, c= 4.46 A)	3180	$[Xe]4f^{14}5d^2 6s^2$	High temperature strength. Corrosion resistance.

Interdiffusion in Multicomponent Alloy System

- **Onsager's formalism* for the Interdiffusion Flux of Component i in a Multicomponent System :**

$$\tilde{J}_i = -\sum_{j=1}^{n-1} \tilde{D}_{ij}^{n} \frac{\partial C_j}{\partial x} \quad (i = 1, 2, \ldots, n-1)$$

where $\partial C_j / \partial x$ is the $(n-1)$ independent concentration gradients

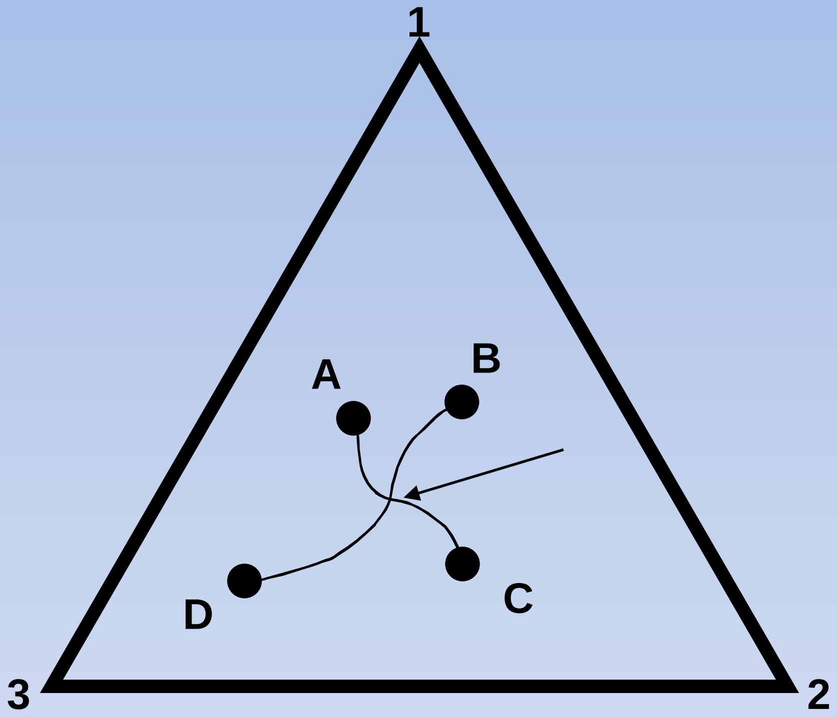
$\tilde{D}_{ij}^{n}$ is the $(n-1)^2$ interdiffusion coefficients

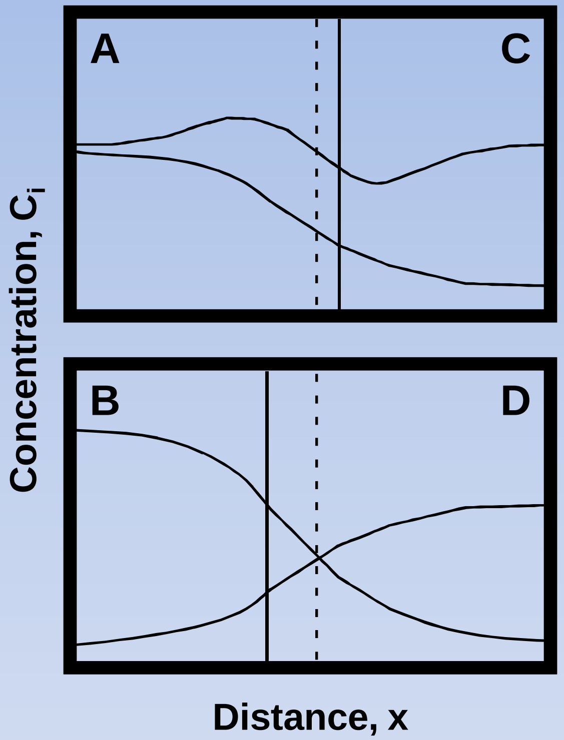
- **Requires Knowledge of (n-1) Independent Concentrations and $(n-1)^2$ Interdiffusion Coefficients.**
- **For a Ternary Systems:**

$$\tilde{J}_1 = -\tilde{D}_{11}^{3} \frac{\partial C_1}{\partial x} - \tilde{D}_{12}^{3} \frac{\partial C_2}{\partial x} \quad \text{and} \quad \tilde{J}_2 = -\tilde{D}_{21}^{3} \frac{\partial C_1}{\partial x} - \tilde{D}_{22}^{3} \frac{\partial C_2}{\partial x}$$

** L. Onsager, Phys. Rev., 37 (1931) 405; 38 (1932) 2265; Ann. NY Acad. Sci., 46 (1965) 241.*

Determination of Ternary Interdiffusion Coefficients: Boltzmann-Matano Analysis*





- Requires Two Independent Diffusion Couples Intersecting at a Common Composition.
- Requires A Significant Number of Diffusion Couple Experiment to Assess Compositional Dependence of Interdiffusion Coefficients.

** J. Kirkaldy, Can. J. Phys., 35 (1957) 435.*

Determination of Interdiffusion Fluxes and Moments of Interdiffusion Fluxes

Interdiffusion Fluxes :

$$\tilde{J}_i = \frac{1}{2t}\int_{C_i(x)}^{C_i(x)} (x - x_o)\,dC_i$$

$$(i = 1,2,\ldots, n)$$

where $t = \text{Time}$

Moments of Interdiffusion Fluxes:

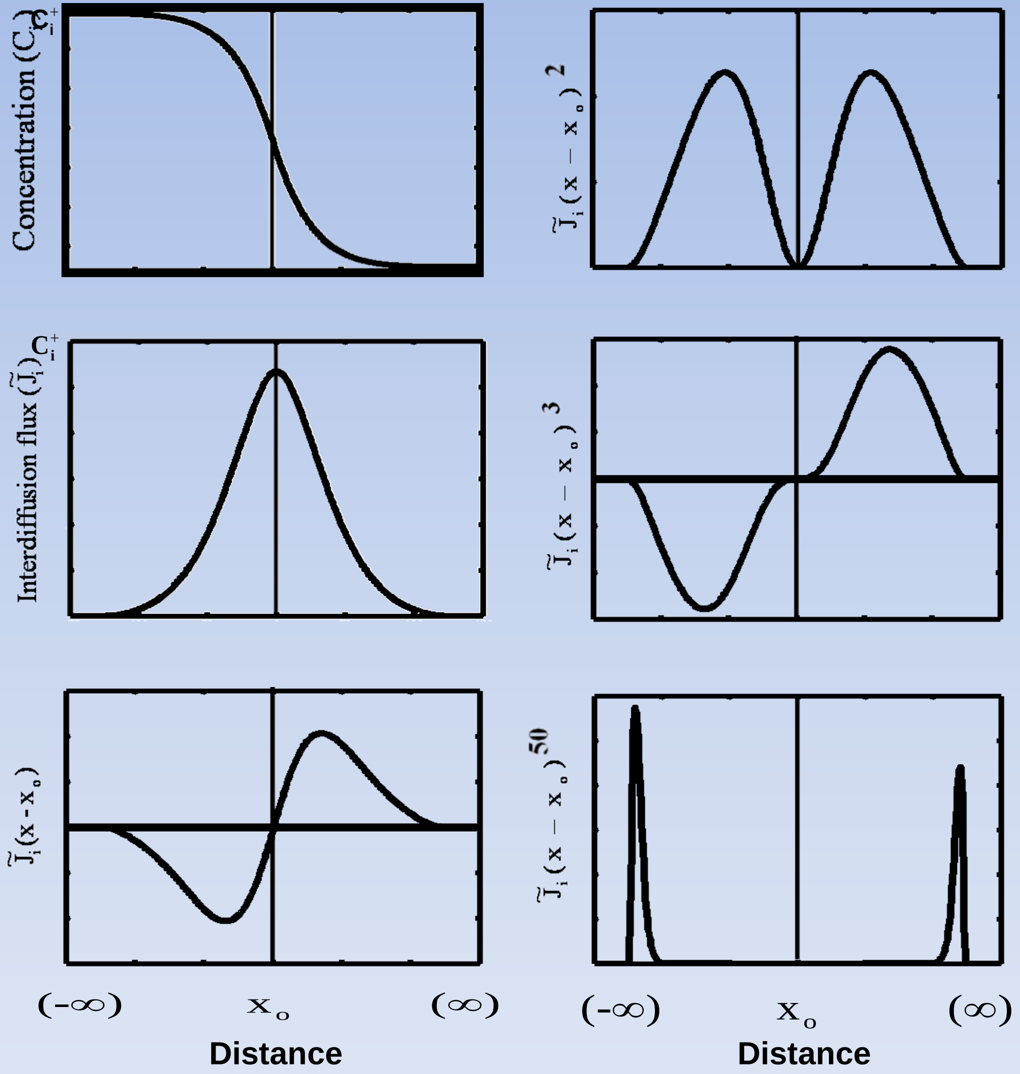
$$M(m) = \int_{x_1}^{x_2} (x - x_o)^m\,dx$$

$$(i = 1,2,\ldots, n)$$

where

$M = $ moment of the interdiffusion flux

$m = $ order of the moment



M. A. Dayananda, C. W. Kim, Metall. Trans., 10A (1979) 1333.
M. A. Dayananda, Y. H. Sohn, Metall. Mater. Trans., 30A (1999) 535.
Y.H. Sohn and M.A. Dayananda, Acta Mater., 48 (2000) 1427.

Refined Approach for the Determination of Average Ternary Interdiffusion Coefficients

$$M(m)=\int_{x_1}^{x_2}\tilde{J}_i(x-x_0)^m\,dx=-\overline{\tilde{D}}_{i1}^{3}\int_{C1(x_1)}^{C2(x_2)}(x-x_0)^m\,dC1-\overline{\tilde{D}}_{i1}^{3}\int_{C1(x_1)}^{C2(x_2)}(x-x_0)^m\,dC1 \qquad (\mathrm{i,j}=1,2)$$

$$M(0)=\int_{x_1}^{x_2}\tilde{J}_i\,dx=-\overline{\tilde{D}}_{i1}^{3}\int_{C1(x_1)}^{C2(x_2)}dC1-\overline{\tilde{D}}_{i1}^{3}\int_{C1(x_1)}^{C2(x_2)}dC1 \qquad (\mathrm{i,j}=1,2)\,(\propto \text{Mass Conservation}^{**})$$

$$M(1)=\int_{x_1}^{x_2}\tilde{J}_i(x-x_0)\,dx=-\overline{\tilde{D}}_{i1}^{3}\int_{C1(x_1)}^{C2(x_2)}(x-x_0)\,dC1-\overline{\tilde{D}}_{i1}^{3}\int_{C1(x_1)}^{C2(x_2)}(x-x_0)\,dC1$$

$$(\mathrm{i,j}=1,2)\,(\propto \text{Centriod of the distribution}^{**})$$

$$M(2)=\int_{x_1}^{x_2}\tilde{J}_i(x-x_0)^2\,dx=-\overline{\tilde{D}}_{i1}^{3}\int_{C1(x_1)}^{C2(x_2)}(x-x_0)^2\,dC1-\overline{\tilde{D}}_{i1}^{3}\int_{C1(x_1)}^{C2(x_2)}(x-x_0)^2\,dC1$$

$$(\mathrm{i,j}=1,2)\,(\propto \text{Moment of inertia or dispersion}^{**})$$

Solutions for 'm=0 and m=1; m=0 and m=2; m=0 and m=3……. m=0 and m=n' independent equations yield series of average ternary interdiffusion coefficients.

**** M. A. Dayananda and Y. H. Sohn, Metall. Mater. Trans., 30A (1999) 535.***
***** R.Ghez, J.D.Fehribach, and G.S.Oehrlein,: J.Electrochem.Soc., 11 (1985) 2759.***

Thermodynamic Stability of Solid Solutions: Constraints for Interdiffusion Coefficients

Based on thermodynamic requirements and the stability of solutions of the diffusion equations, the four ternary interdiffusion coefficients should satisfy relations (*, **)

Requirement: $\overline{\tilde{D}}_{11}^{3} > 0 \qquad \overline{\tilde{D}}_{22}^{3} > 0$

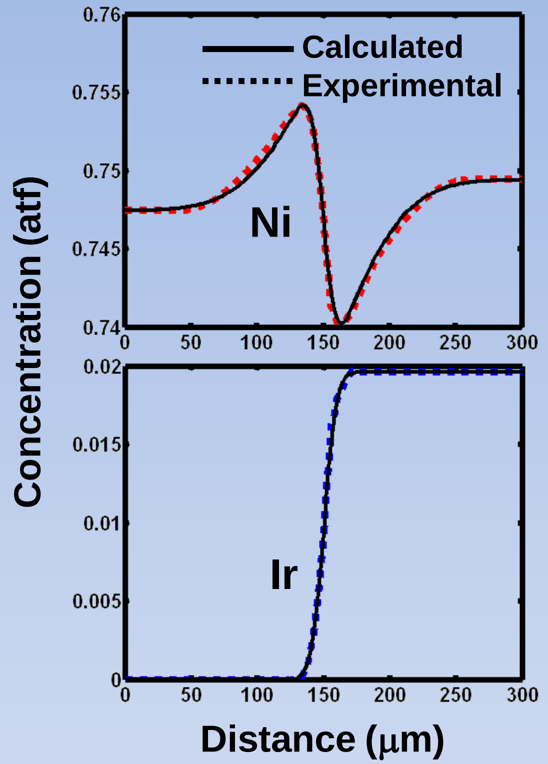
Constraint 1: $\overline{\tilde{D}}_{11}^{3} + \overline{\tilde{D}}_{22}^{3} > 0$

Constraint 2: $\left(\overline{\tilde{D}}_{11}^{3}\overline{\tilde{D}}_{22}^{3} - \overline{\tilde{D}}_{12}^{3}\overline{\tilde{D}}_{21}^{3}\right) \geq 0$

Constraint 3: $\left(\overline{\tilde{D}}_{11}^{3} + \overline{\tilde{D}}_{22}^{3}\right)^{2} - 4\left(\overline{\tilde{D}}_{11}^{3}\overline{\tilde{D}}_{22}^{3} - \overline{\tilde{D}}_{12}^{3}\overline{\tilde{D}}_{21}^{3}\right) \geq 0$

**   Kirkaldy, J.S., Weichert, D., Zia-Ul-Haq: Can J. Phys. 41 (1963) 2166*
*** Kirkaldy, J.S.: In: Adv. In Mater. Res., Vol.4, Herman, H.(ed) New York: Interscience Publishers, 1970, p. 55.*

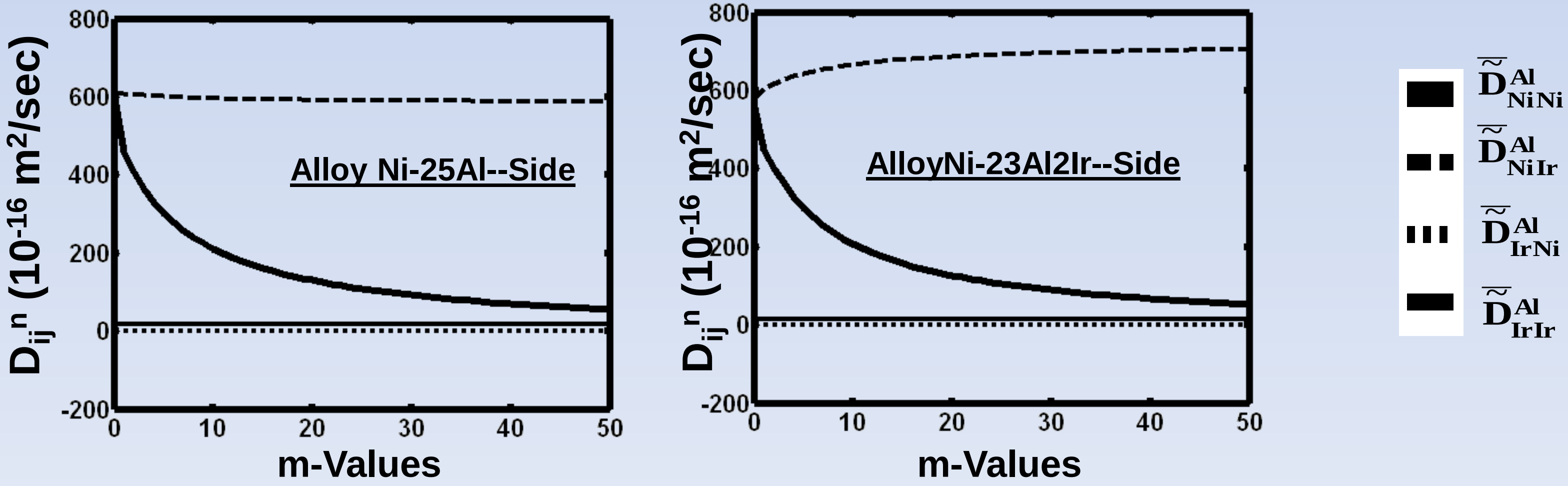
Average Ternary Interdiffusion Coefficients: Ni-25Al vs. Ni-23Al-2Ir



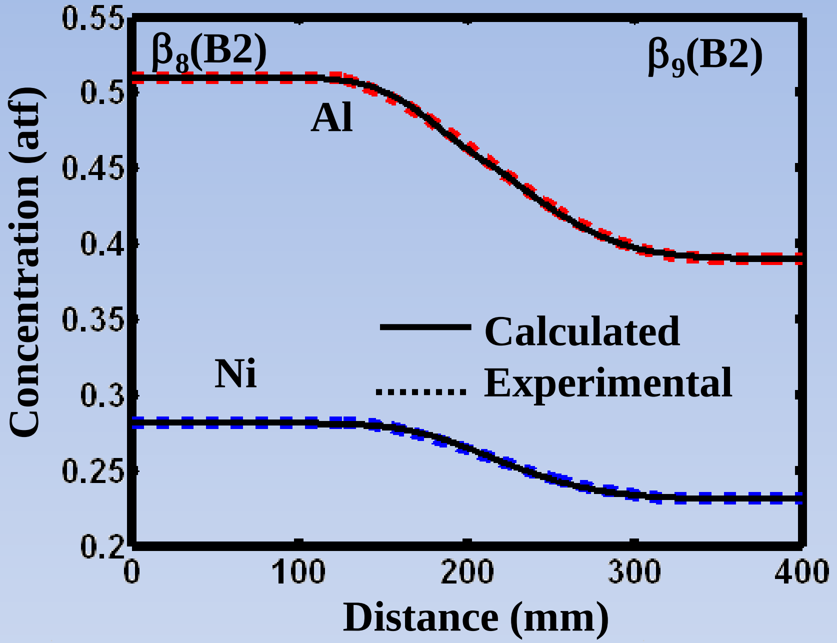
$10^{-14}\ m^2/sec$

Range	$(C^{-\infty} - C^{0})$	$(C^{0} - C^{+\infty})$
$\overline{\tilde{D}}^{Al}_{NiNi}$	5.96	5.56
$\overline{\tilde{D}}^{Al}_{NiIr}$	6.12	5.78
$\overline{\tilde{D}}^{Al}_{IrNi}$	Negligible	Negligible.
$\overline{\tilde{D}}^{Al}_{IrIr}$	0.16	0.16

Refined approach at m=0



Refined Approach for Alloy β_8 vs Alloy β_9

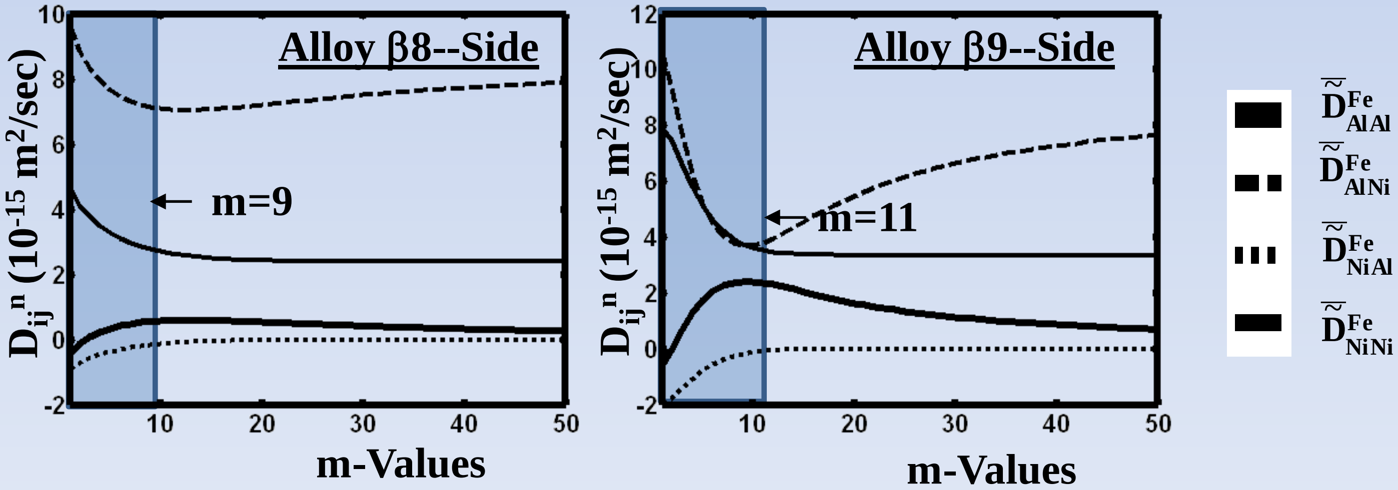


$10^{-15}\ m^2/sec$

Range	$(C^{-\infty} - C^0)$	$(C^0 - C^{+\infty})$
$\tilde{D}^{Fe}_{AlAl}$	0.6 (1.6)	2.4 (2.7)
$\tilde{D}^{Fe}_{AlNi}$	7.1(1.7)	3.8(1.7)
$\tilde{D}^{Fe}_{NiAl}$	Ngl. (Ngl.)	Ngl. (Ngl.)
$\tilde{D}^{Fe}_{NiNi}$	2.8 (1.6)	3.5 (1.6)

Refined approach at m=9 & m=11

** Boltzmann-Matano Analysis



* *T.D. Moyer and M.A.Dayananda, Metall. Mater. Trans., 7A (1976) 1035-40.*

Experimental Details

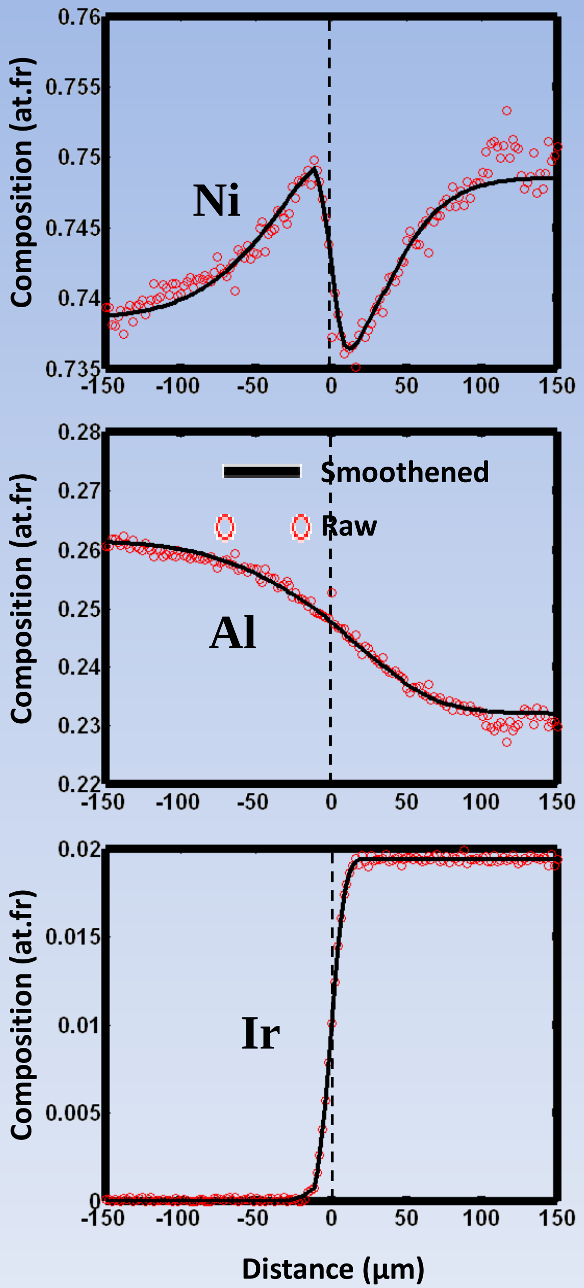
- **Alloy casting by arc-melting and drop-cast. Elemental purity (99.97%Ni, 99.9%Al and 99.2%X by weight).**
- **Homogenization heat treatment at 1200°C for 137 hours.**

Series	Diffusion Couples
Ir-based	Ni-25Al vs. Ni-23.5Al-1Ir
	Ni-24.5Al vs. Ni-24.5Al-1Ir
	Ni-26Al vs. Ni-23Al-2Ir
	Ni-25Al vs. Ni-23Al-3Ir
	Ni-24Al vs. Ni-24Al-2Al
	Ni-24Al vs. Ni-23Al-3Ir
Ta-based	Ni-24.5Al vs. Ni-23Al-1.5Ta
	Ni-25Al vs. Ni-23Al-1.5Ta
	Ni-26Al vs. Ni-23Al-1.5Ta
Re-based	Ni-24Al vs. Ni-24.5Al-0.5Re
	Ni-25Al vs. Ni-23.5Al-0.5Re
	Ni-26Al vs. Ni-23Al-0.7Re

- **Assembled with Si_3N_4 Jigs.**
- **Bonded for 0.5hrs at 1200°C in a vacuum furnace.**
- **Encapsulated in evacuated quartz capsule.**
- **Diffusion anneal at 1200°C for 4.5 hours followed by water quenching.**
- **Metallographic preparation and Microstructural analysis.**
- **Compositional analysis by electron probe microanalysis (EMPA).**

- **JEOL (JXA-8900) electron probe microanalyzer (EPMA) at NIMS:**
  - ✓ **20 KeV accelerating voltage and 52 nA probe current.**
  - ✓ **Pure Standards of Ni, Al, Ir, Ta and Re along with ZAF corrections**

Typical Concentration Profiles

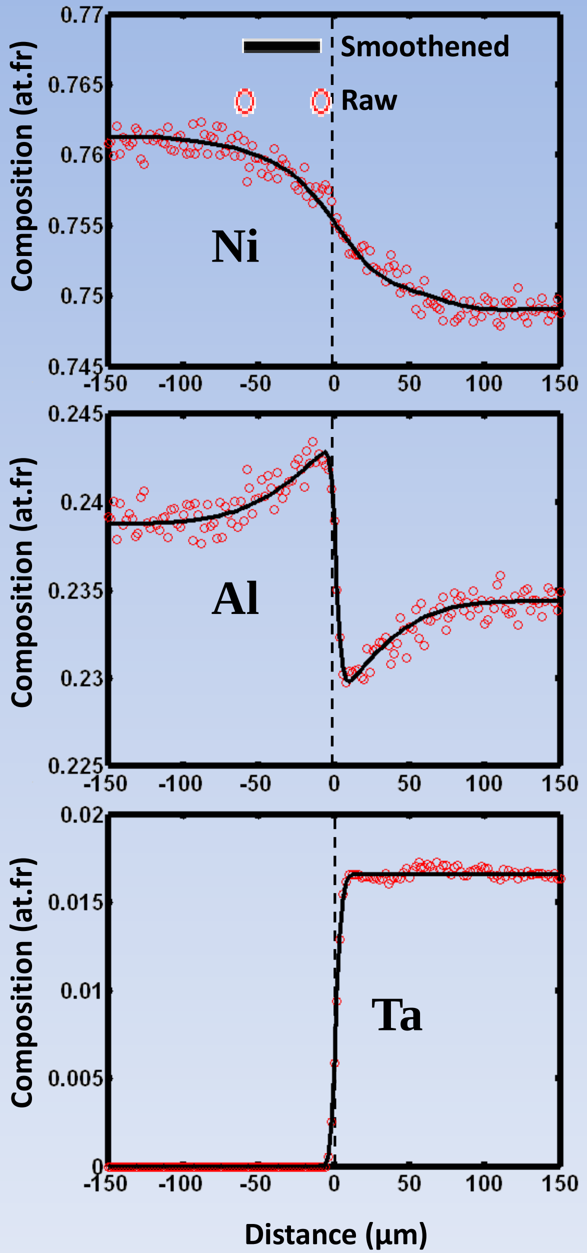


Ni-26Al vs. Ni-23Al-2Ir at 1200°C for 5 hours

	$\overline{\tilde{D}}^{Ni}_{AlAl}$	$\overline{\tilde{D}}^{Ni}_{AlX}$	$\overline{\tilde{D}}^{Ni}_{XAl}$	$\overline{\tilde{D}}^{Ni}_{XX}$	$\overline{\tilde{D}}^{Al}_{NiNi}$	$\overline{\tilde{D}}^{Al}_{NiX}$	$\overline{\tilde{D}}^{Al}_{XNi}$	$\overline{\tilde{D}}^{Al}_{XX}$
$(C_i^{-\infty}-C_i^0)$	871.4	-52.0	Neg.	15.4	871.4	912.1	Neg.	16.4
$(C_i^0-C_i^{+\infty})$	591.5	-117.3	Neg.	13.0	591.5	690.2	Neg.	12.3

- **Interdiffusion flux of Ir against the concentration gradient of Al increased the interdiffusion flux of Al.**
- **Interdiffusion flux of Ir significantly influenced the interdiffusion flux of Ni:**
  - **Large positive $\overline{\tilde{D}}^{Al}_{NiIr}$**
  - **Suggest a significant diffusional Interaction between Ni and Ir via α-site preference.**

Typical Concentration Profiles

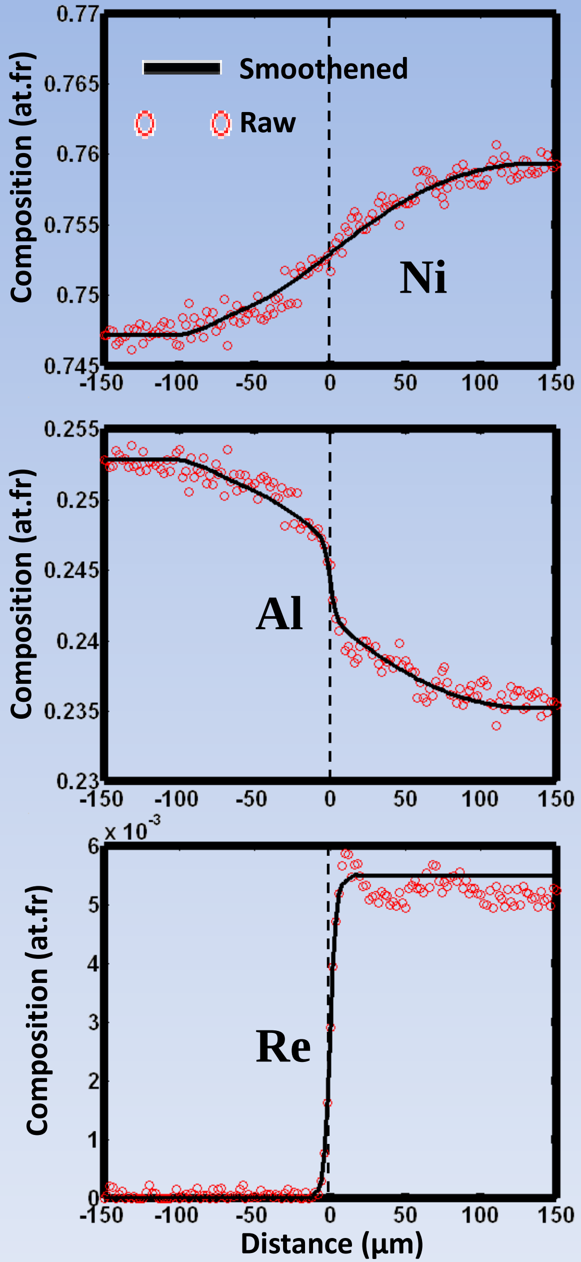


Ni-24.5Al vs. Ni-23Al-1.5Ta at 1200°C for 5 hours

	$\bar{\tilde{D}}^{Ni}_{AlAl}$	$\bar{\tilde{D}}^{Ni}_{AlX}$	$\bar{\tilde{D}}^{Ni}_{XAl}$	$\bar{\tilde{D}}^{Ni}_{XX}$	$\bar{\tilde{D}}^{Al}_{NiNi}$	$\bar{\tilde{D}}^{Al}_{NiX}$	$\bar{\tilde{D}}^{Al}_{XNi}$	$\bar{\tilde{D}}^{Al}_{XX}$
$(C_i^{-\infty}-C_i^{0})$	608.6	530.1	Ngl.	3.2	607.8	74.6	Ngl.	3.3
$(C_i^{0}-C_i^{+\infty})$	485.1	453.7	Ngl.	2.6	485.1	28.9	Ngl.	2.6

- **Interdiffusion flux of Ta caused an uphill-diffusion of Al and decreased the interdiffusion flux of Al down its concentration gradient.**
    - **Large positive** $\bar{\tilde{D}}^{Al}_{AlTa}$
    - **Suggest a significant diffusional Interaction between Al and Ta via β-site preference.**
- **Interdiffusion flux of Ta caused an increase in Ni interdiffusion flux slightly.**

Typical Concentration Profiles



Ni-25Al vs. Ni-23.5Al-0.5Re at 1200°C for 5 hours

	$\tilde{\bar{D}}^{Ni}_{AlAl}$	$\tilde{\bar{D}}^{Ni}_{AlX}$	$\tilde{\bar{D}}^{Ni}_{XAl}$	$\tilde{\bar{D}}^{Ni}_{XX}$	$\tilde{\bar{D}}^{Al}_{NiNi}$	$\tilde{\bar{D}}^{Al}_{NiX}$	$\tilde{\bar{D}}^{Al}_{XNi}$	$\tilde{\bar{D}}^{Al}_{XX}$
$(C_i^{-\infty}-C_i^{0})$	572.8	320.0	Ngl.	4.1	572.8	249.0	Neg.	4.1
$(C_i^{0}-C_i^{+\infty})$	728.1	450.6	Ngl.	5.0	728.1	272.4	Neg.	5.1

- Interdiffusion flux of Re against the concentration gradient of Al decreased the interdiffusion flux of Al.
  - ✓ Positive $\tilde{\bar{D}}^{Al}_{AlRe}$
  - ✓ A diffusional Interaction between Al and Re via β-site preference.
- Interdiffusion flux of Re increased the interdiffusion flux of Ni.
  - ✓ Positive $\tilde{\bar{D}}^{Al}_{NiRe}$

Average Ternary Interdiffusion Coefficients

Diffusion Couple	Composition Range	Average Ternary Interdiffusion Coefficients (10^{-16}m^2/sec)				Average Ternary Interdiffusion Coefficients (10^{-16} m^2/sec)			
		$\tilde{D}^{Ni}_{AlAl}$	$\tilde{D}^{Ni}_{AlX}$	$\tilde{D}^{Ni}_{XAl}$	$\tilde{D}^{Ni}_{XX}$	$\tilde{D}^{Al}_{NiNi}$	$\tilde{D}^{Al}_{NiX}$	$\tilde{D}^{Al}_{XNi}$	$\tilde{D}^{Al}_{XX}$
Ni-25Al vs. Ni-23.5Al-1Ir (X=Ir)	$(C_i^{-\infty}-C_i^{0})$	782.2	-101.2	Ngl.	13.5	784.4	873.2	Ngl.	13.9
	$(C_i^{0}-C_i^{+\infty})$	647.1	-101.3	Ngl.	13.8	644.9	730.9	Ngl.	13.4
Ni-24.5Al vs. Ni-24.5Al-1Ir (X=Ir)	$(C_i^{-\infty}-C_i^{0})$	541.0	-84.7	Ngl.	10.5	540.9	615.1	Ngl.	10.6
	$(C_i^{0}-C_i^{+\infty})$	816.9	-75.7	Ngl.	19.1	814.4	870.9	Ngl.	21.6
Ni-26Al vs. Ni-23Al-2Ir (X=Ir)	$(C_i^{-\infty}-C_i^{0})$	871.4	-52.0	Ngl.	15.4	874.5	912.1	Ngl.	16.4
	$(C_i^{0}-C_i^{+\infty})$	591.5	-117.3	Ngl.	13.0	587.8	690.2	Ngl.	12.3
Ni-25Al vs. Ni-23Al-2Ir (X=Ir)	$(C_i^{-\infty}-C_i^{0})$	522.0	-107.3	Ngl.	16.4	521.9	612.8	Ngl.	16.5
	$(C_i^{0}-C_i^{+\infty})$	494.0	-116.6	Ngl.	15.9	493.8	594.5	Ngl.	16.1
Ni-25Al vs. Ni-23Al-3Ir (X=Ir)	$(C_i^{-\infty}-C_i^{0})$	440.9	-92.8	Ngl.	15.1	439.4	522.0	Ngl.	16.3
	$(C_i^{0}-C_i^{+\infty})$	441.2	-135.5	Ngl.	19.3	441.9	548.0	Ngl.	19.2
Ni-24Al vs. Ni-24Al-2Ir (X=Ir)	$(C_i^{-\infty}-C_i^{0})$	255.5	15.0	8.1	14.1	263.6	234.6	-8.1	5.9
	$(C_i^{0}-C_i^{+\infty})$	315.0	10.1	47.6	20.5	285.1	244.1	-23.2	0.5

Average Ternary Interdiffusion Coefficients

Diffusion Couple	Composition Range	Average Ternary Interdiffusion Coefficients (10^{-16} m^2/sec)				Average Ternary Interdiffusion Coefficients (10^{-16} m^2/sec)			
		$\tilde{D}^{Ni}_{AlAl}$	$\tilde{D}^{Ni}_{AlX}$	$\tilde{D}^{Ni}_{XAl}$	$\tilde{D}^{Ni}_{XX}$	$\tilde{D}^{Al}_{NiNi}$	$\tilde{D}^{Al}_{NiX}$	$\tilde{D}^{Al}_{XNi}$	$\tilde{D}^{Al}_{XX}$
Ni-24.5Al vs. Ni-23Al-1.5Ta (X=Ta)	$(C_i^{-\infty}-C_i^{0})$	608.6	530.1	Ngl.	3.2	607.8	74.6	Ngl.	3.3
	$(C_i^{0}-C_i^{+\infty})$	485.1	453.7	Ngl.	2.6	485.1	28.9	Ngl.	2.6
Ni-25Al vs. Ni-23Al-1.5Ta (X=Ta)	$(C_i^{-\infty}-C_i^{0})$	281.1	267.3	Ngl.	3.4	281.5	10.7	Ngl.	3.1
	$(C_i^{0}-C_i^{+\infty})$	338.8	320.0	Ngl.	1.8	338.9	17.4	Ngl.	1.7
Ni-26Al vs. Ni-23Al-1.5Ta (X=Ta)	$(C_i^{-\infty}-C_i^{0})$	413.9	381.0	Ngl.	3.4	415.3	30.0	Ngl.	3.4
	$(C_i^{0}-C_i^{+\infty})$	445.0	391.9	Ngl.	5.6	443.7	46.8	Ngl.	5.4
Ni-25Al vs. Ni-23.5Al-0.5Re (X=Re)	$(C_i^{-\infty}-C_i^{0})$	572.8	320.0	Ngl.	4.1	572.8	249.0	Ngl.	4.1
	$(C_i^{0}-C_i^{+\infty})$	728.1	450.6	Ngl.	5.0	728.1	272.4	Ngl.	5.1
Ni-24.5Al vs. Ni-23.5Al-0.7Re (X=Re)	$(C_i^{-\infty}-C_i^{0})$	592.3	553.9	Ngl.	4.3	592.3	34.1	Ngl.	4.4
	$(C_i^{0}-C_i^{+\infty})$	450.2	399.7	Ngl.	3.5	450.2	47.0	Ngl.	3.4
Ni-26Al vs. Ni-23Al-0.7Re (X=Re)	$(C_i^{-\infty}-C_i^{0})$	491.2	371.5	Ngl.	7.0	491.2	112.8	Ngl.	7.0
	$(C_i^{0}-C_i^{+\infty})$	461.6	343.0	Ngl.	3.9	461.6	114.7	Ngl.	3.9

Comparison of Average Ternary Interdiffusion Coefficients with Ternary Interdiffusion Coefficicents Determined by Boltzmann-Matano Analysis

Diffusion Couple	Intersecting Composition	Average Ternary Interdiffusion Coefficients (10^{-16} m^2/sec)				Ternary Interdiffusion Coefficients (10^{-16} m^2/sec)			
		$\overline{\tilde{D}}{}^{Ni}_{AlAl}$	$\overline{\tilde{D}}{}^{Ni}_{AlX}$	$\overline{\tilde{D}}{}^{Ni}_{XAl}$	$\overline{\tilde{D}}{}^{Ni}_{XX}$	$\tilde{D}^{Ni}_{AlAl}$	$\tilde{D}^{Ni}_{AlX}$	$\tilde{D}^{Ni}_{XAl}$	$\tilde{D}^{Ni}_{XX}$
Ni-25Al vs. Ni-23.5Al-1Ir (X=Ir)	Ni-23.9Al-1.8Ir	782.2	-101.2	Ngl.	13.5	797.7	-11.4	Ngl.	14.6
		647.1	-101.3	Ngl.	13.8				
Ni-24.5Al vs. Ni-24.5Al-1Ir (X=Ir)	Ni-24.5Al-0.1Ir	541.0	-84.7	Ngl.	10.5	858.8	-21.7	Ngl.	12.6
		816.9	-75.7	Ngl.	19.1				
Ni-26Al vs. Ni-23Al-2Ir (X=Ir)	Ni-24.1Al-0.4Ir	871.4	-52.0	Ngl.	15.4	562.1	-30.0	15.9	15.8
		591.5	-117.3	Ngl.	13.0				

Summary

- **Influence of Ir, Ta and Re alloying additions on the interdiffusion behavior of Ni_3Al ($L1_2$) alloys were examined at 1200°C.**

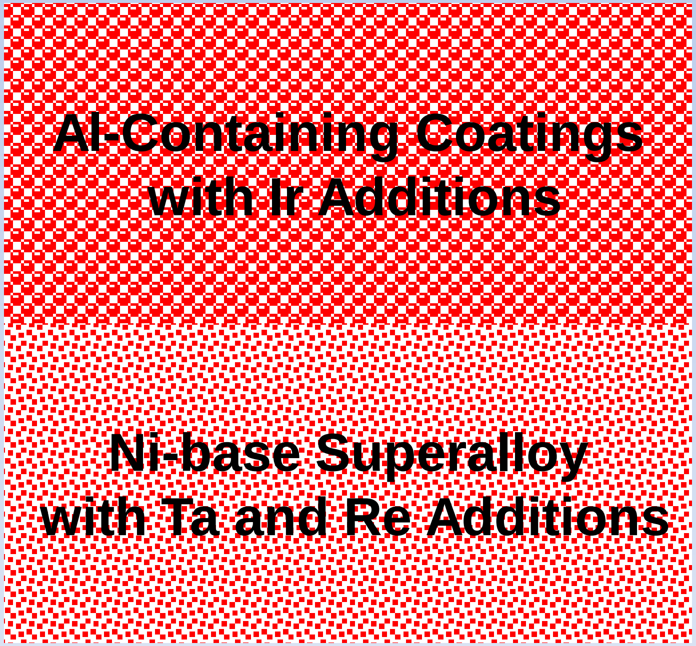
- **Consistent results obtained by ternary interdiffusion coefficients determined by Boltzmann-Matano analysis and average ternary interdiffusion coefficients determined by examining the moments of interdiffusion fluxes.**

Summary

- **Ir, Ta and Re diffuse slowly (e.g., two orders of magnitude smaller than Ni or Al):**
- **Large Positive** $\overline{\tilde{D}}^{Al}_{AlRe}$ **and** $\overline{\tilde{D}}^{Al}_{AlTa}$ **for Ta and Re that Prefer to Substitute Al in β-sublattice.**
- **Small Positive** $\overline{\tilde{D}}^{Al}_{NiRe}$ **and** $\overline{\tilde{D}}^{Al}_{NiTa}$ **for Ta and Re.**
- **Large Positive** $\overline{\tilde{D}}^{Al}_{NiIr}$ **for Ir that Prefer to Substitute Ni in α-sublattice.**
- **Small Negative** $\overline{\tilde{D}}^{Al}_{AlIr}$ **for Ir.**

Additional Consideration

- **Proper alloying of Ni-base superalloys and protective coatings can significantly reduce the interdiffusion flux of Al into the Ni-base superalloy.**



Al-Containing Coatings with Ir Additions

Ni-base Superalloy with Ta and Re Additions

Acknowledgements

National Science Foundation (NSF) CAREER Award:

Multicomponent-Multiphase Diffusion (DMR-0238356).

UNIVERSITY OF CENTRAL FLORIDA

FROM PROMISE TO PROMINENCE
CELEBRATING 40 YEARS