Improving the Weldability of Fe-Al-Cr Alloys Through TiC Additions

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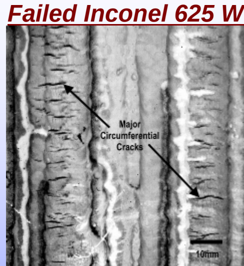
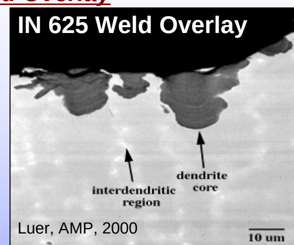
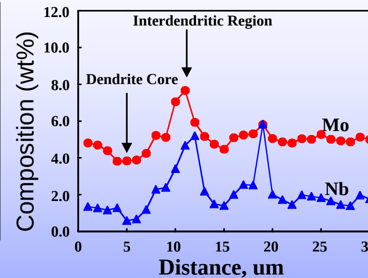
Advantages of FeCrAl Weld Overlays Over Currently Used Alloys in Low NOx Combustion Conditions

Failed Inconel 625 Weld Overlay







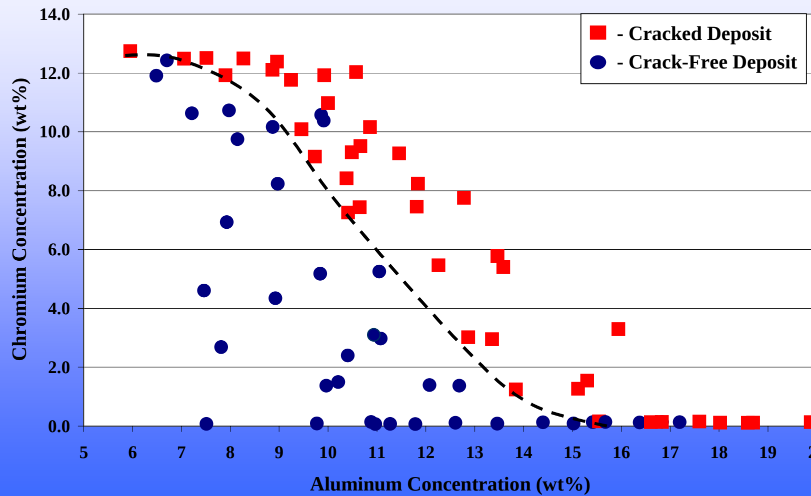
- **Cracking in overlay**
- **Preferential attack due to microsegregation**
- **Initiation sites for corrosion-fatigue cracking**

Drawbacks of Austenitic Overlays:
- Expensive: $15-$20/lb
- Exhibit microsegregation and preferential corrosion
- Susceptible to corrosion-fatigue cracking

Use of Fe-Al-Cr Weld Overlays:
- Low cost: ~ $5-10/lb
- No residual microsegregation
- Excellent corrosion resistance in sulfur bearing environments
- Weldability is limited

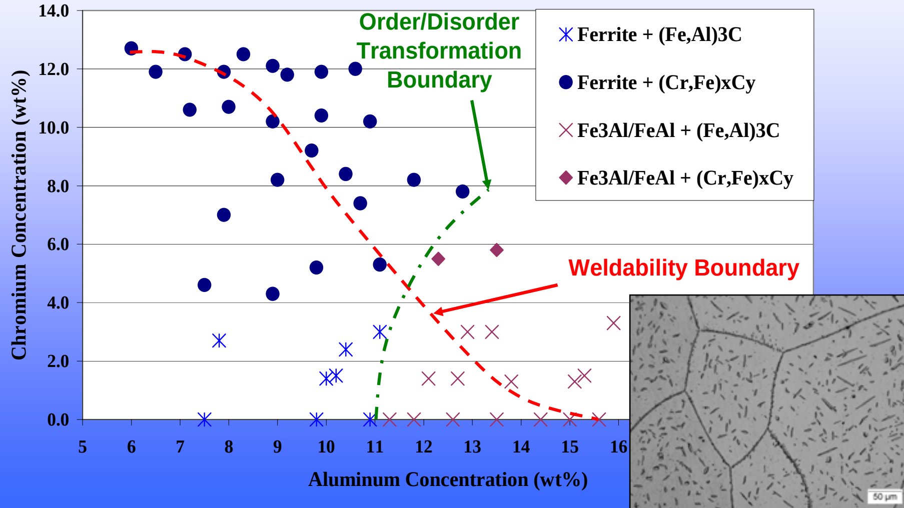
Previous Weldability Results

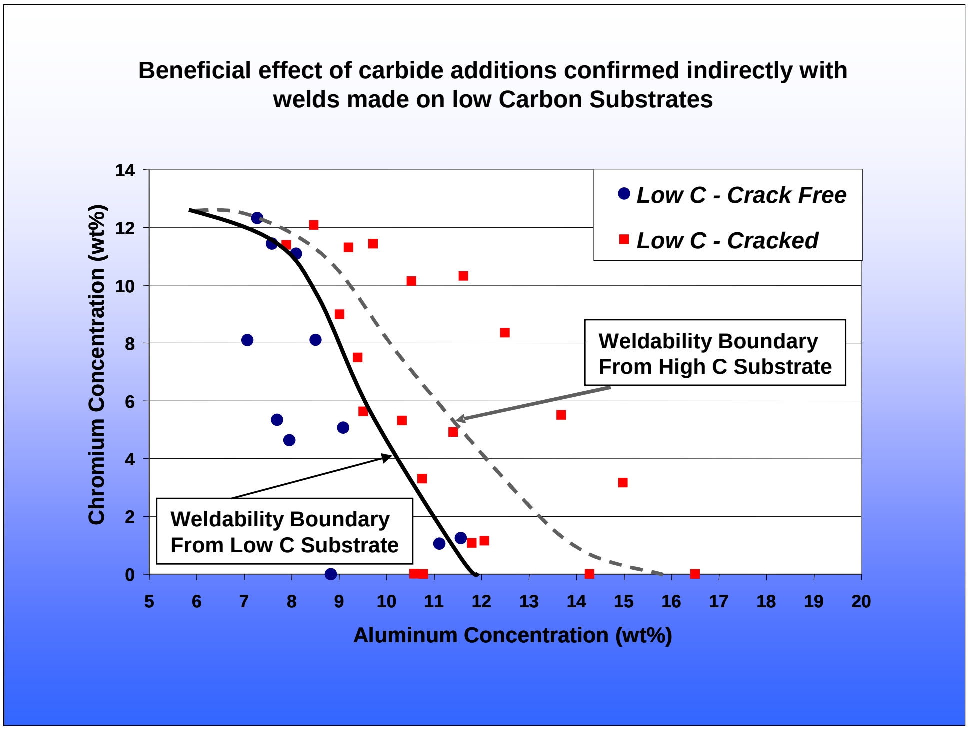
- Deposition of crack-free welds well beyond 11 wt% Al were possible



Previous Weldability Results

- Deposition of crack-free welds well beyond 11 wt% Al were possible
- Improved cracking resistance attributed to formation of $(Fe,Al)_3C$ carbides that act as Hydrogen trap sites




Beneficial effect of carbide additions confirmed indirectly with
welds made on low Carbon Substrates
Low C - Crack Free
Low C - Cracked
Weldability Boundary
From High C Substrate
Weldability Boundary
From Low C Substrate
Chromium Concentration (wt%)
Aluminum Concentration (wt%)
0
2
4
6
8
10
12
14
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

Technical Approach

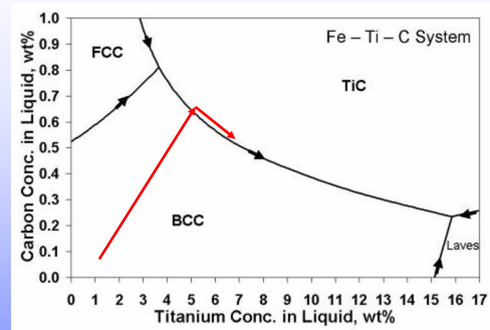
TiC in steels:

TiC has high binding energy with H_2

Trapping Locations	Binding Energy (kJ / mol)	Reference
Dislocation	0 – 59	Choo & Lee 1982, Hirth 1980
Grain boundary	18 – 59	Choo & Lee 1982, Kumnick 1980
MnS	72	Lee & Lee 1983
Al_2O_3	79	Lee & Lee 1986
Y_2O_3	80	Maroef & Olson 1999
TiC	87 – 98	Lee & Lee 1984, Pressouyre & Bernstein 1978

TiC in Fe-Ti-C system:

TiC can form in situ during solidification



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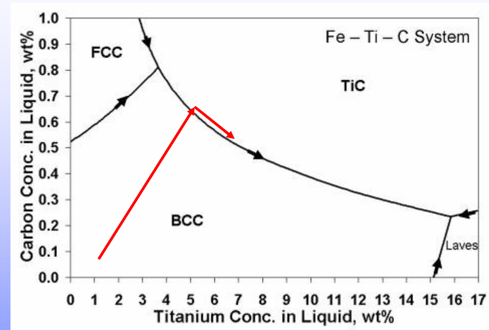


Overall Objective:

Utilize TiC additions to improve the weldability of FeCrAl weld overlays

Need to:

- **Establish method for controlling TiC contents (liquidus projection for FeCrAlTiC system and solidification model for predicting/controlling primary solidification path)**
- **Verify improvements to weldability**
- **Ensure corrosion resistance is not adversely affected**

Approach

Solidification Modeling

- **Calculate liquidus projections using Thermo-Calc**
- **Develop a solute redistribution model for determining TiC content from knowledge of nominal composition and cooling rate**
- **Validate with experimental alloys and phase ID**

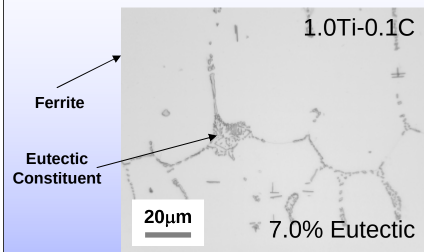
Weldability Testing

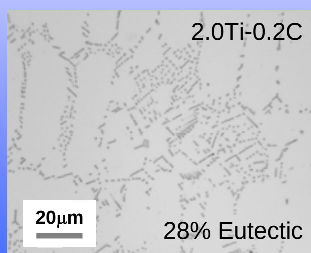
- **Confirm effectiveness of TiC for mitigating cracking**
- **Welds prepared with a range of Al, Cr, and TiC contents**

Corrosion Testing

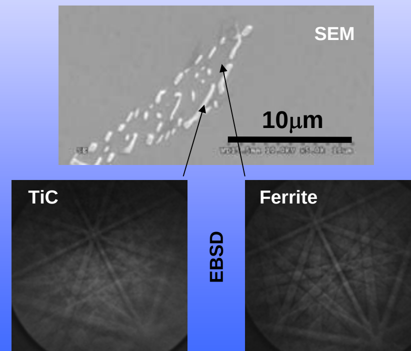
- **Thermo gravimetric analysis in simulated Low NOx combustion gas**

Experimental Alloy Microstructures / Phase ID





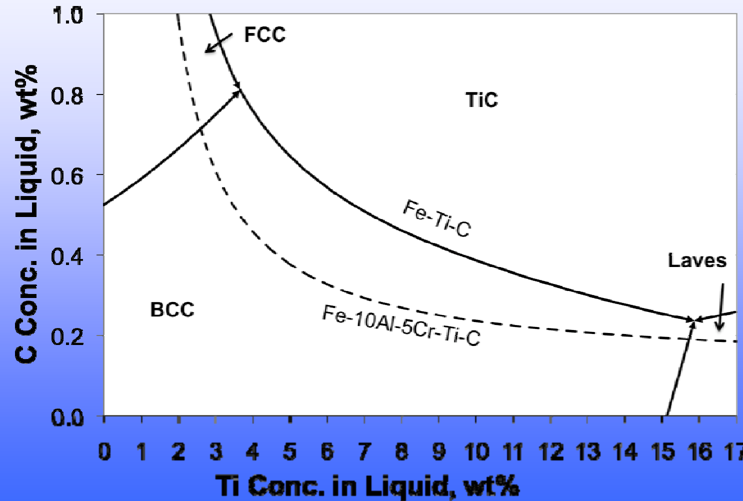
(wt%)	Ti	C
Fe-10Al-5Cr	1.0	0.1
Fe-10Al-5Cr	1.0	0.5
Fe-10Al-5Cr	1.5	0.4
Fe-10Al-5Cr	2.0	0.1
Fe-10Al-5Cr	2.0	0.2



Calculated Liquidus Projection

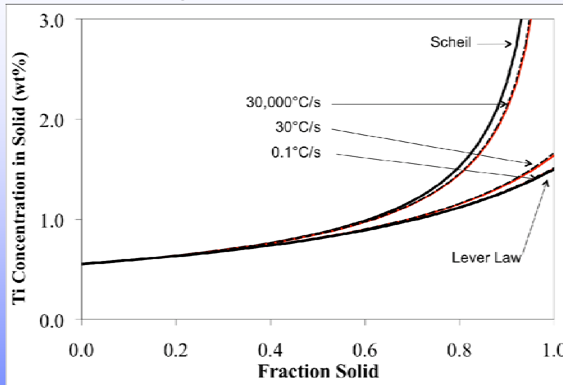
•Additions of Al and Cr to Fe affect position of the eutectic line

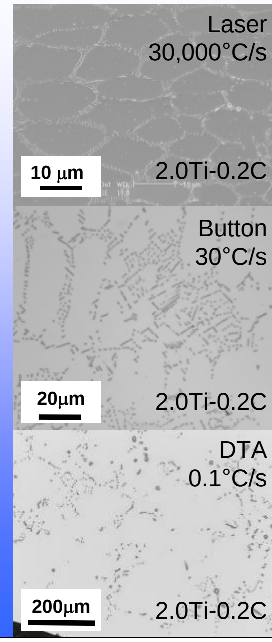
•Additions of Al and Cr lower solubility of Ti and C in Fe, as expected



Assessing Solute Redistribution Behavior

Influence of cooling rate on redistribution of Ti

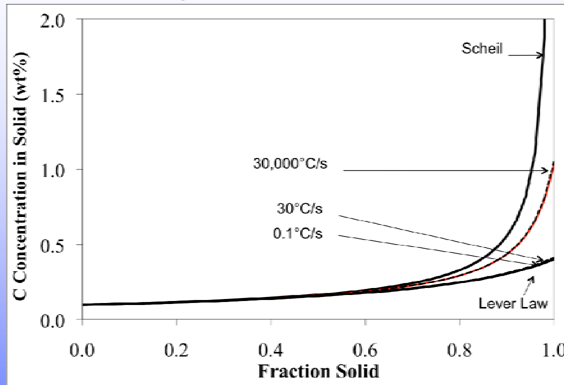


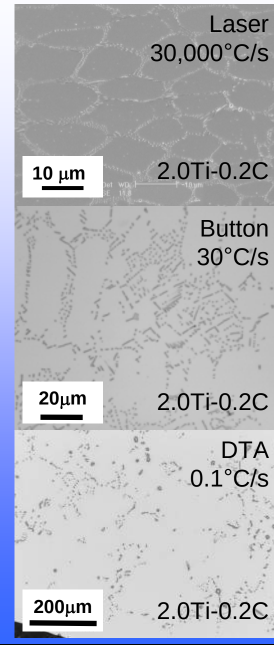


- S. Kobayashi (ISIJ 1988) solute redistribution model
- Range of solute redistribution does not permit use of simplified solidification path calculations (based on the lever law or Scheil approximations)

Assessing Solute Redistribution Behavior

Influence of cooling rate on redistribution of C





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Solidification Path Calculations

Need to account for cooling rate and effect on back diffusion in the solid

Adapting Kobayashi's Solute Redistribution Model (ISIJ 1988) for Solidification Path:

$$C_L^i = C_o^i \xi^{\frac{k^i - 1}{1-\beta k^i}} \left\{ 1 + \Gamma \left[\frac{1}{2}\left(\frac{1}{\xi^2} - 1 \right) - 2\left(\frac{1}{\xi} - 1 \right) - \ln \xi \right] \right\}$$

$$\xi = 1 - \left(1 - \beta k^i\right)\left(1 - f_L\right)$$

$$\beta = \frac{4\alpha}{1 + 4\alpha}$$

$$\alpha = \frac{D_{Fe}^i t_f}{L^2} = \frac{D_{Fe}^i \Delta T}{\varepsilon L^2}$$

← Solute ability to diffuse

← Distance needed to diffuse

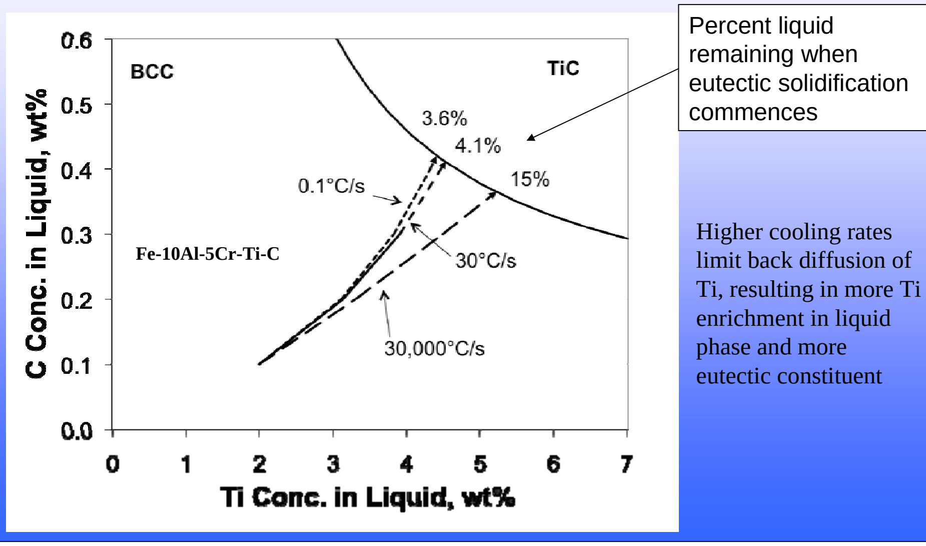
Brody-Flemings (AIME 1966)

Steps in Model

- Starting at f_L = *1 at nominal composition*
- Solve for f_L for a target solute C_L value
- Insert f_L into C_L for other solute element
- Increase target C_L and repeat to define path

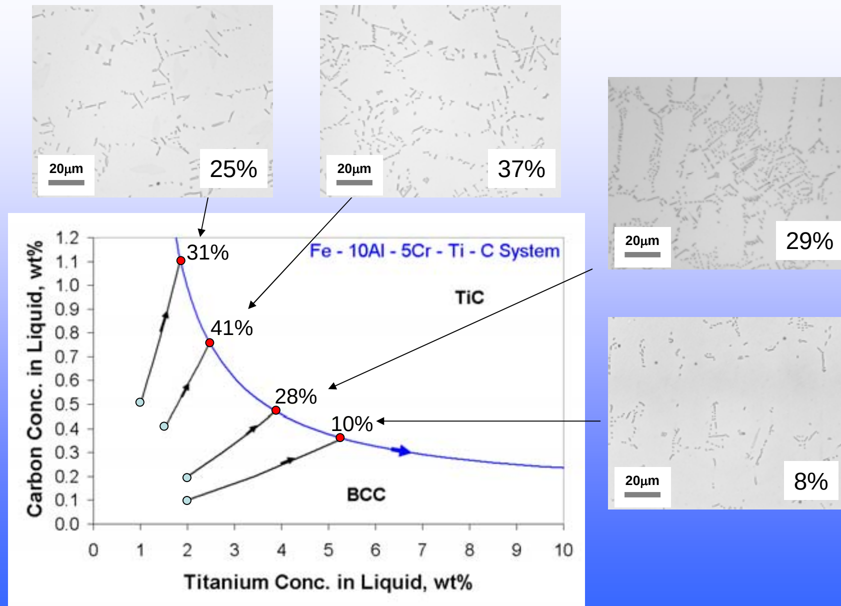
Example Solidification Path Calculations

- Solute redistribution model developed to account for back diffusion of solute elements
- Based on Kobayashi model
- First known ternary solidification path model that accounts for back diffusion



Higher cooling rates limit back diffusion of Ti, resulting in more Ti enrichment in liquid phase and more eutectic constituent

Comparison of Model and Experimental Results



Weldability Testing

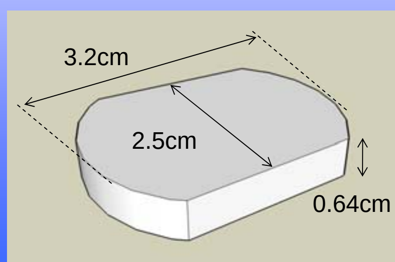
Gas Tungsten Arc Welding
- 200 amps
- 12 volts
- 2.8 mm arc gap
- 5 mm/s travel speed
- Cooling rate ~10^2°C/s
- Shielding gas:
  - Argon
  - Argon – 5% Hydrogen

Effect of Al and Cr

(wt%) (%)

Fe	Al	Cr	Ti	C	% TiC
Bal.	5.0	2.0	2.0	0.3	7.7
Bal.	7.5	3.5	2.0	0.3	6.9
Bal.	10.0	5.0	2.0	0.2	4.7
Bal.	12.5	6.5	2.0	0.2	5.1
Bal.	15.0	8.0	1.5	0.2	3.9
Bal.	17.5	9.5	1.5	0.2	4.5
Bal.	20.0	11.0	1.5	0.2	3.9

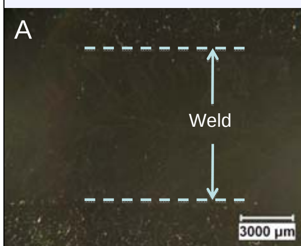
* Ti and C chosen for TiC Contents of 4 – 7 %



Fe-15Al-8Cr-1.5Ti-0.2C

Weldability: Effect of TiC

- Ground, polished, etched
- Stereomicroscope Images

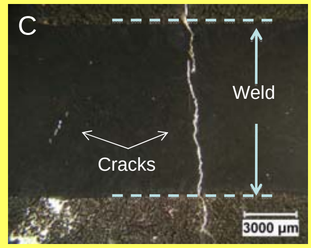


Shielding Gas:
Argon

Composition:
Fe-10Al-5Cr-0.05C

0% TiC

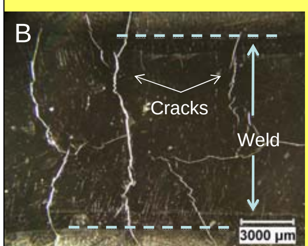
Hydrogen in Shielding Gas



Shielding Gas:
Argon/Hydrogen Mix

Composition:
Fe-10Al-5Cr-1Ti-0.1C

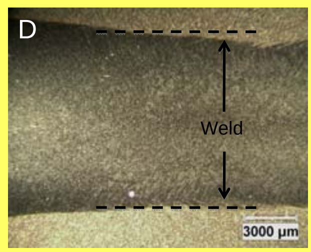
2.2% TiC



Shielding Gas:
Argon/Hydrogen Mix

Composition:
Fe-10Al-5Cr-0.05C

0% TiC

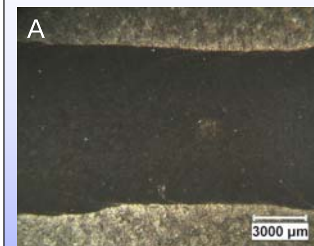


Shielding Gas:
Argon/Hydrogen Mix

Composition:
Fe-10Al-5Cr-1.5Ti-0.4C

5.7% TiC

Weldability: Effect of Al and Cr

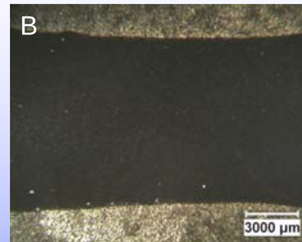


Shielding Gas:
Argon/Hydrogen Mix

Composition:
Fe-**5Al-2Cr**-2Ti-0.3C

7.7% TiC

No Cracks

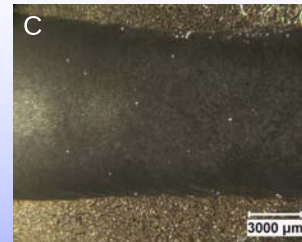


Shielding Gas:
Argon/Hydrogen Mix

Composition:
Fe-**10Al-5Cr**-2Ti-0.2C

4.7% TiC

No Cracks



Shielding Gas:
Argon/Hydrogen Mix

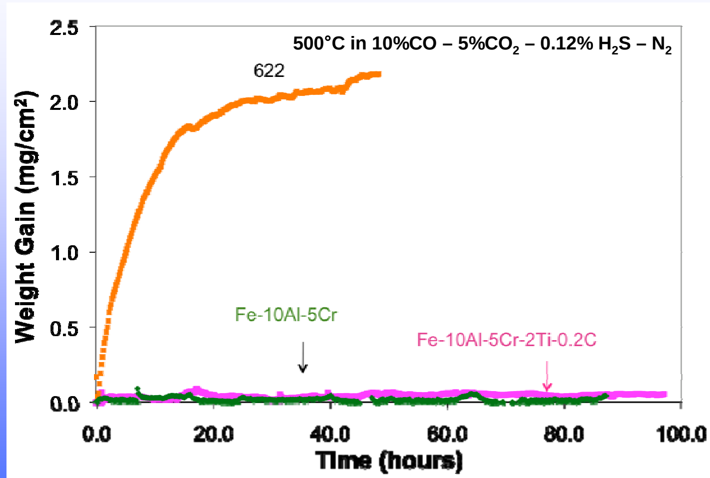
Composition:
Fe-**20Al-11Cr**-1.5Ti-0.2C

3.9% TiC

No Cracks

Corrosion Resistance

- Thermo gravimetric Analysis:



- Corrosion resistance slightly decreases when TiC present
- Corrosion resistance remains significantly better than Ni-based overlay

Major Project Accomplishments

- A solidification model was developed and validated for controlling the TiC content of Fe-Cr-Al-Ti-C weld overlays
- Resistance to hydrogen cracking in welds was shown to significantly improve with TiC additions
- Corrosion resistance is not significantly affected