# Image Cover Sheet

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**TITLE**

Laser Cladding of Ni-Al Bronze for Repairing Marine Components

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# Laser Cladding of Ni-Al Bronze for Repairing Marine Components

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## ABSTRACT

Laser cladding of conventional Ni-Al bronze onto a bronze substrate by using welding wire has been investigated. The laser cladding was conducted with a 3 kW $CO_2$ laser with a simultaneous feeding of the Ni-Al bronze wire into the molten pool. The clad geometry and microstructure depended on the laser processing parameters. With optimized processing conditions, a relatively uniform and smooth clad layer was obtained. The hardness of clad layer was substantially higher than that of the substrate. The microstructure and composition of laser clad layer was studied with scanning electron microscope (SEM) and energy disperse spectroscopy of x-ray (EDS). The macro and micro stresses of laser clad layer were investigated with x-ray diffraction (XRD) technique. The electrochemical polarization testing in 3.5 % NaCl solution showed that the corrosion resistance of laser clad coating was similar to that of the substrate material.

## Contents:

- *Introduction*
- *Experimental Details*
- *Results and Discussion*
- *Conclusions*

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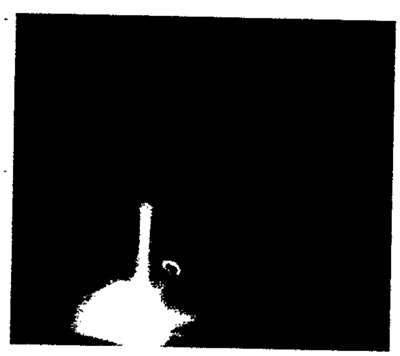
## Introduction

**Laser Cladding:**

- A process to create a layer of desired material on the substrate surface by melting the surface as well as the clad material with a focused laser beam.

**Advantages:**

- Produces a fully dense coating with metallurgical bonding to the substrate - no peeling or debonding problems.
- Modifies substrate surface composition selectively to improve its surface related properties.
- Can functionally repair local damage with minimised heat effect.



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## Introduction

**Supply of Clad Materials:**

- Pre-placed thin strip or paste.
- Continuous feeding of powder or wire.

**Continuous Wire Feeding Technique:**

- Not widely investigated.
- Cleaner process compared to powder feeding method.
- Ni-Al welding wires are commercially available.

**Objective:**

- To investigate laser cladding process with continuous feeding of Ni-Al bronze wires for the repair of marine components.

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## Experimental Details - Materials

Substrate Material:

- UNS C95800 Cast Ni-Al Bronze (Cu8.6%Al-4.8%Ni4.0%Fe1.1%Mn)

Clad Material:

- Ni-Al Bronze welding wire (Cu9.0%Al4.6%Ni-3.9%Fe1.2%Mn), 0.254 mm in diameter.

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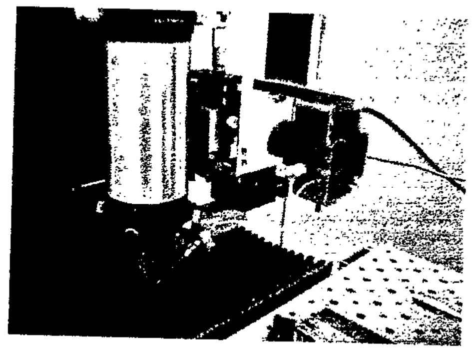
## Experimental Set-Up

- 3 kw $CO_2$ laser with a 190 mm focal length lens.
- Power density: (6 - 9.5) x $10^4$ w/cm$^2$.
- Traversing speed: 5 - 20 mm/s.
- Wire feeder rate: 50 - 200 mm/sec.
- 4-axis motion system: x, y, z and rotary.



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## Experimental Details
## - Specimen Evaluation

Metallurgical Evaluation

- Optical microscope, microhardness, SEM, EDS & XRD analysis.

XRD Residual Stress Measurement

- Conventional $Sin^2\Psi$ method.
- Measure (331) peak shift.
- Ni-filtered *CuK*$\alpha$ X-ray irradiation with 40 kV / 55 mA.

Corrosion Test

- Electrochemical polarization in 3.5% NaCl solutions at 1mV/sec scan speed.

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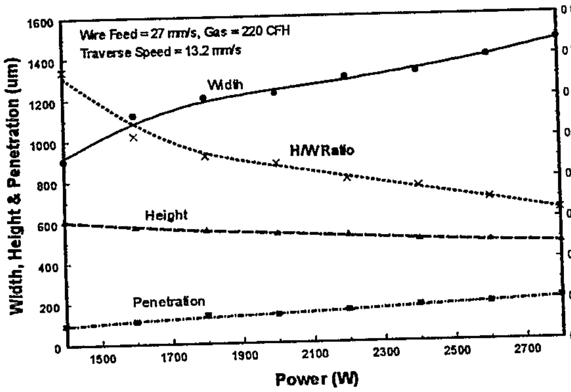
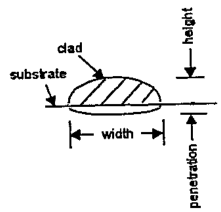
## Results: Effect of Laser Power on the Geometry of the Single Clad Bead

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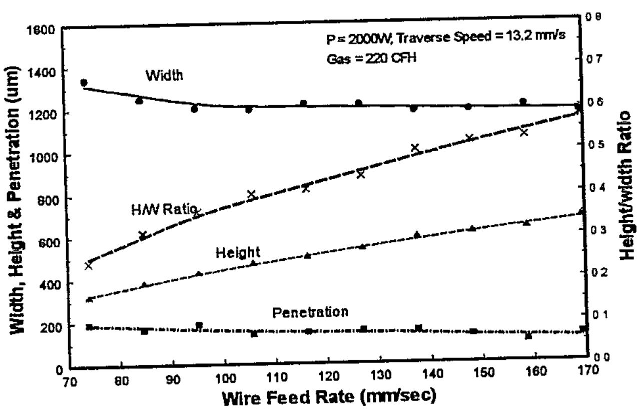
## Effect of Wire Feed Rate on the Geometry of the Single Clad Bead

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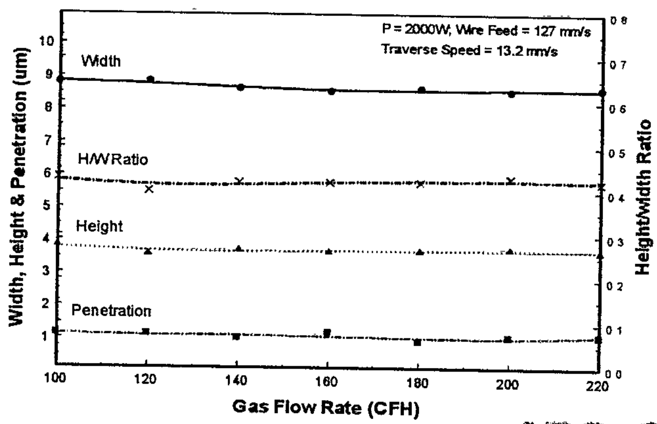
## Effect of Shielding Gas Flow on the Geometry of the Single Clad Bead

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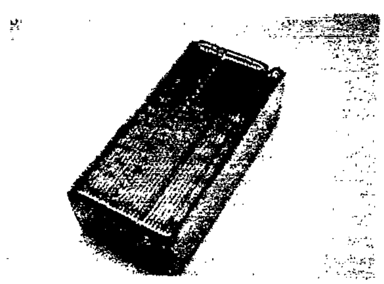
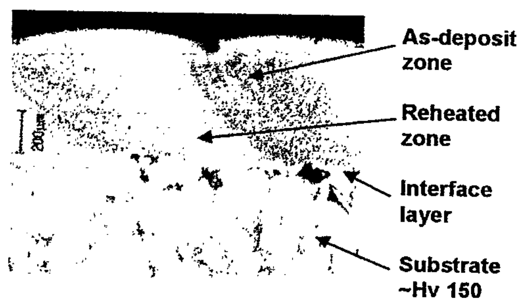
## Laser Clad Ni-Al Bronze Coating on Bronze Substrate



(a) Overall View of Clad Layer




(b) Cross-Sectional View

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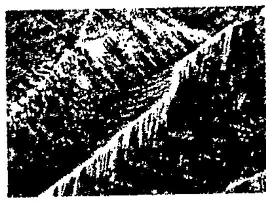
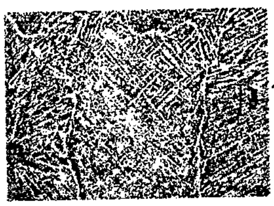
## Microstructure of Laser Clad Ni-Al Bronze with 150 J/mm Heat Input



As-Deposited Zone (x1000), ~ Hv 370



Reheated Zone (x1000), ~ Hv 310


Ni-Al Bronze Clad Layer (150 J/mm), x50

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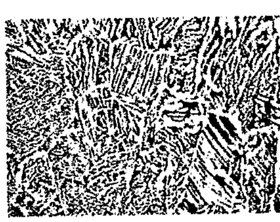
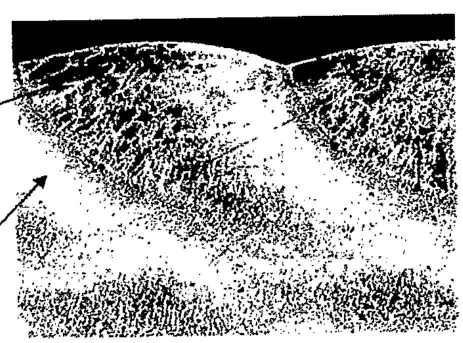
## Microstructure of Laser Clad Ni-Al Bronze with 350 J/mm Heat Input

As-Deposited Zone (x1000), ~ Hv 330



Reheated Zone (x1000), ~ Hv 260



Ni-Al Bronze Clad Layer (350 J/mm), x50

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## Comparison of Hardness in Laser Clad Coatings with Different Heat Input

| Region | Average Micro-Hardness, $Hv_{200}$ | |
|---|---|---|
| | 150 J/mm Heat Input | 350 J/mm Heat Input |
| As-Deposited Zone | 370 | 330 |
| Reheated Zone | 310 | 260 |
| Substrate | 150 | |

- The laser clad Ni-Al bronze coating with 150 J/mm heat input has higher hardness compared with that with 350 J/mm heat input.

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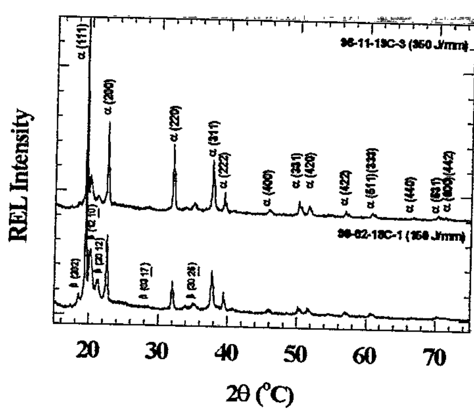
## Phase Identification of Laser Clad Ni-Al Bronze Coatings with X-Ray Diffraction




- Zr-filtered Mo$K\alpha$ x-ray irradiation was used for the measurement.
- No significant difference in the x-ray diffraction patterns of two coatings with different heat inputs.
- Both have majority of $\alpha$ phase plus small amount of $\beta^*$ phase.

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## Detailed Phase Analysis of Laser Clad Ni-Al Bronze Coatings

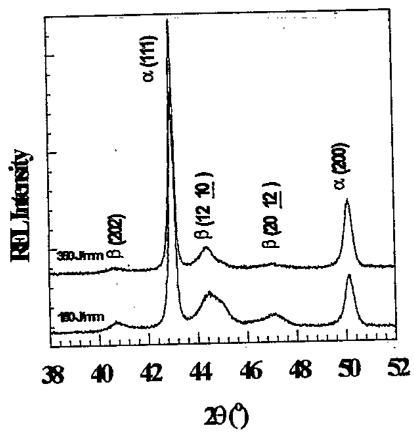



Table: Comparison of Relative Intensities of Diffracted Lines

| Relative Intensity of Phase (hkl) | 150 J/mm Heat Input | 350 J/mm Heat Input |
|---|---|---|
| α(111)/α(111) | 1.0 | 1.0 |
| β(202)/α(111) | 0.10 | 0.06 |
| β(1210)/α(111) | 0.70 | 0.34 |
| β(2012)/α(111) | 0.27 | 0.11 |
| α(200)/α(111) | 0.36 | 0.46 |

- The amount of β* phase in Ni-Al bronze coating with 150 J/mm heat input is higher than that in the coating with 350 J/mm heat input.

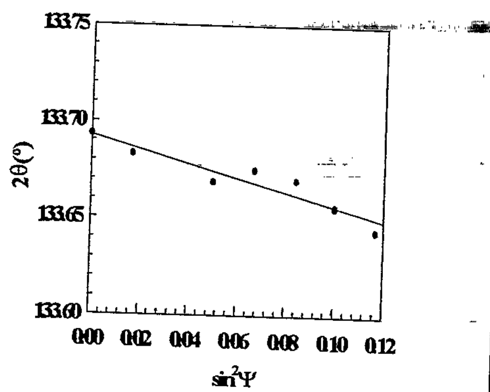
## Comparison of Micro-Strains of Laser Clad Ni-Al Bronze Coatings

| (hkl) | Lattice Strain (%) | |
|---|---|---|
| | 150 J/mm Heat Input | 350 J/mm Heat Input |
| α(200) | 0.228 | 0.141 |
| α(220) | 0.146 | 0.107 |

- The lattice strain (micro-strain) is measured by x-ray diffraction method (peak broadening) with Zr-filtered *MoKα* radiation.
- The micro-strain of α phase in Ni-Al bronze coating clad with 150 J/mm heat input is higher than that in the coating with 350 J/mm heat input.

## Surface Macro Residual Stress Evaluation of Laser Clad Ni-Al Bronze with XRD

- $Sin^2\Psi$ method was used to measure the peak shift of (331) plane.
- Ni-filtered *CuK*α x-ray irradiation with 40 kV / 55 mA.
- Assuming bulk E ≈ 130 GPa, ν = 0.3.

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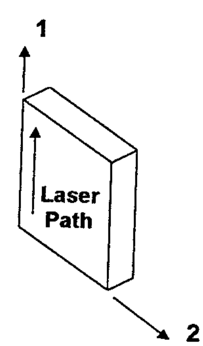
## Surface Residual Stress Measurements of Laser Clad Ni-Al Bronze with XRD

For 350 J/mm heat input:
$\sigma_1$ = 149 ± 26 MPa
$\sigma_2$ = 133 ± 22 MPa
For 150 J/mm heat input:
$\sigma_1$ = 133 ± 30 MPa
$\sigma_2$ = 138 ± 28 MPa

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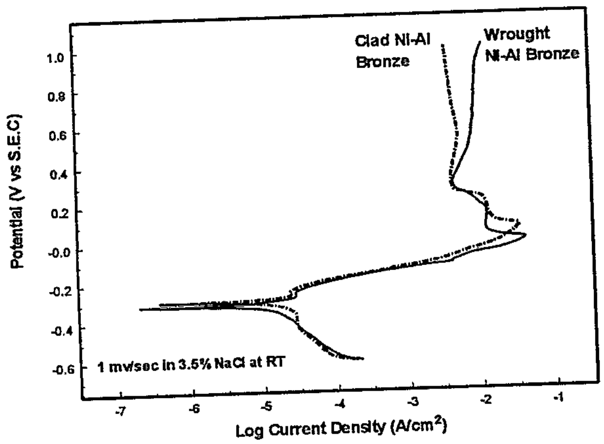
## Comparison of Electrochemical Polarisation Curves in 3.5 % NaCl Solution




- The polarization curve of the laser clad coating is similar to that of the substrate bronze.

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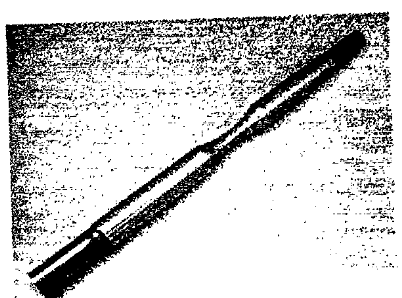
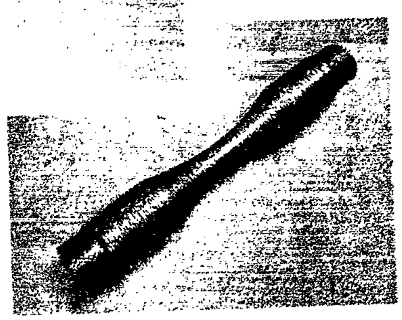
## Laser Cladding of Corrosion Fatigue Samples



Steel substrate



Bronze substrate

- The surface of laser clad Ni-Al bronze coating on the corrosion fatigue sample is smooth.

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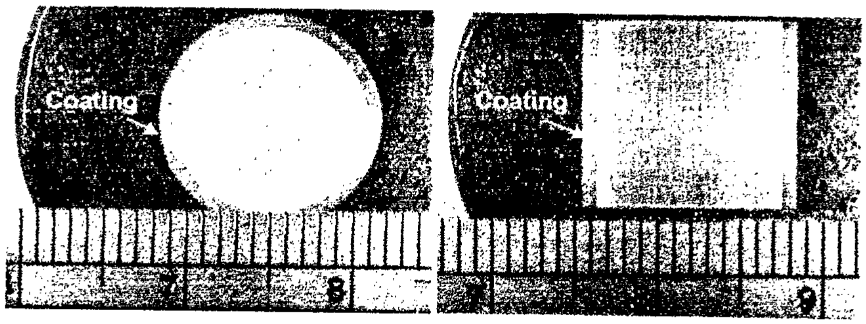
## Cross-Sectional Views of Clad Ni-Al Bronze Coating on Corrosion Fatigue Sample




(a) Perpendicular direction

(b) Axial direction

• The Ni-Al bronze coating is uniform, free of porosity and cracking.

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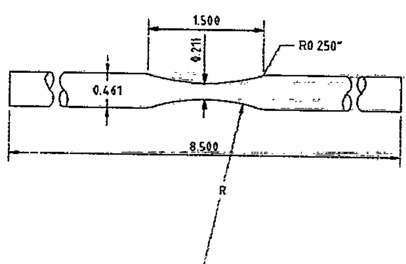
## Hardness of Ni-Al Bronze Coating on Corrosion Fatigue Samples

- The substrate dimension of the corrosion fatigue sample is relatively small.
- The hardness of Ni-Al bronze coating at the reduced section is significantly reduced due to the limited heat sink effect.
- The hardness of Ni-Al bronze coating at the area can increase with additional cooling methods.




The substrate dimension of corrosion fatigue sample before cladding.

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## *Effect of Cooling Methods on the Coating Hardness of Corrosion Fatigue Samples*

**Hardness Measured at Reduced Section**

| Cooling Method | Average Micro-Hardness, $Hv_{200}$ | |
|---|---|---|
| | As-Deposited Zone | Reheated Zone |
| No Additional Cooling | 234 | 216 |
| End Cooled with Liquid Nitrogen | 261 | 248 |
| Internal Water Cooling | 362 | 240 |

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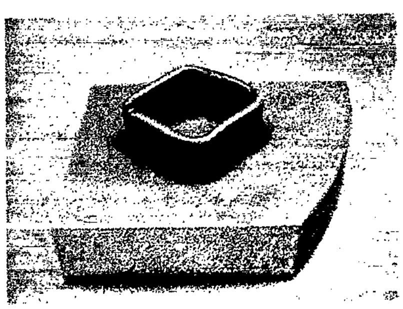
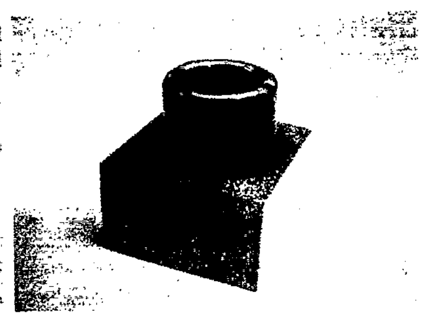
## *Samples of Laser Consolidation of Ni-Al Bronze*





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## Conclusions

- With optimized processing parameters, a uniform and crack-free Ni-Al bronze coating can be clad onto bronze substrate with a $CO_2$ laser and continuous wire feeding.
- The laser clad Ni-Al bronze coating is harder than substrate. However, the coating hardness is significantly affected by the laser heat input as well as the substrate cooling effect.

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## Conclusions

- In 3.5% NaCl solution, the polarization curve of the laser clad coating is similar to that of the substrate bronze.
- The laser cladding process can be used for repairing marine components, while the laser consolidation process can be used to build features on the components or produce functional rapid prototype parts for marine applications.

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## *Acknowledgements*


- The authors would like to thank Jon Fenner for his significant contribution in process development.
- Thanks are also expressed to Andrew Chen, Glen Campbell, Andre Theriault and Mike Meinert for their numerous contributions for the work.


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