Recent Advances in Titanium Fabrication Technology for Naval Applications

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Outline

- Benefits
- Titanium Alloys
- Current and Potential Applications
- Cost Reduction Efforts
- Summary

Benefits

- Weight savings (increased payload, range, and speed)
- 30+ years of corrosion free life
- Excellent fire resistance
- Enhanced stealth (reduced magnetic signatures)
- Compatibility with organic composites

Titanium Alloys

ASTM Grade	Gr 1	Gr 2	Gr 9	Gr 5
Alloy	Ti-CP	Ti-CP	Ti-3Al-2.5V	Ti 6Al-4V
Property*				
Tensile Strength, min, ksi	35	50	90	130
Yield Strength, min, ksi	25	40	70	120
Elongation, min, %	24	20	15	10
Composition, wt%				
Nitrogen, max	0.03	0.03	0.05	0.05
Carbon, max	0.10	0.10	0.10	0.10
Hydrogen, max	0.015	0.015	0.015	0.015
Iron, max	0.20	0.30	0.25	0.40
Oxygen, max	0.18	0.25	0.15	0.20
Aluminum			3.5-4.5	5.5-6.75
Vanadium			2.0-3.0	3.5-4.5

Ti-5111 Alloy

Ti 5Al-1V-1Sn-1Zr-.8Mo

- Developed in the late 1980's in conjunction with US Navy as a tough, weldable, high strength titanium alloy
- Equivalent corrosion resistance to Ti-CP grade 2 or Ti-6-4 ELI titanium
- No SCC concerns in sea water
- Displays highest toughness of any high strength Ti alloy
- Commercially available since late 1990's (>400,000 lbs)
- Currently focus of Navy/CTC project to certify Ti-5111 for critical ship and submarine applications

Ti-5111 - Specifications

- ASTM Standard Specifications:
  - ASTM B265 - Titanium Alloy Strip, Sheet, and Plate
  - ASTM B348 - Titanium Alloy Bars and Billets
  - ASTM B 381 – Forgings
  - ASTM B 863 – Wire
  - ASTM F467/F467M - Nonferrous Nuts
  - ASTM F468/F468M - Nonferrous Bolts, Hex Cap Screws, and Studs
- AWS A5.16, Grade ERTi-32 Filler Metal

Applications will be in plate, pipe, bar, castings, forgings, & fasteners

Ti-5111 – Sub HDR Mast

- MSI approved by NAVSEA
- Welded Ti-5111 structure – uses plate, bar, forging & weld wire
- Fabrication to “near” NAVSEA Tech. Pub. S9074-AR-GIB-010/278 requirements
- Over 30 masts in service/first deployed in 2000

HDR Mast

Ti-5111 - MMADCP

- Support approval and certification for critical applications in surface ships and submarines
- Characterize the mechanical & physical properties of Ti-5111 plate, bar, forgings, castings and weldments (weld metal & HAZ)
- Ti-5111 products under evaluation:
  - ¼, ½, 1, and 2 inch thick plates focus on welded plates (GTAW)
  - ½, 1, 2, 3½, and 4 inch diameter bar
  - 8-inch diameter forging
  - Graphite mould & Investment cast plates
- Draft NAVSEA Technical Publication, "Requirements for Titanium & Titanium Alloys for Ship and Submarine Applications"

Current Ship Application

- Seawater Cooling
  - Ti-CP heat exchangers (newer classes)
- Seawater Service
  - Ti-CP/Ti 6-4 firemain pumps (newer classes)
  - Ti-CP seawater piping (LPD-17)

NGSS Avondale Titanium Fabrication Facility for Piping Subassemblies

Current Ship Applications

- Structures
  - Ti 3-2.5 exhaust uptakes (DDG-53 and higher)
  - Ti 3-2.5 prototype door and hatch

Ti Door on DDG-51

Ti Hatch on DDG-51

Fabrication Cost Drivers

Material

- Thermochemical reduction (Kroll)
- Batch processing
- Vacuum arc re-melting of ingots - 2 to 3 times for quality

Welding

- Specialized gas shielding
- Low productivity welding processes
- Labor intensive joint designs and preparation procedures

- ***High fabrication costs relative to steel and aluminum alloys limit applications***

New Opportunities

- Island Structure
- Flight Deck Plates
- Doors
- Sponsons
- Elevator Platforms
- Armor Protection
- Firemain Piping
- Storage Tanks

CVN-21 Conceptual Drawing

Other Platforms: DD(X), LHA(R), LCS, Legacy Ship Upgrades

Titanium Thrust

- Goal
  - As-fabricated costs equivalent to stainless steel and Cu-Ni alloys

- Challenge
  - Develop lower cost processing technologies
  - Develop higher productivity welding processes to join large structures in a shipyard environment
  - Optimize fatigue, ductility, and toughness of welded structures and ballistic resistance

Process Technologies

- Lower cost process technologies enabled by emerging extraction, ingot melting & manufacturing methods
  - DARPA Titanium Initiative
  - Single melt processes
  - Superplastic forming/diffusion bonding

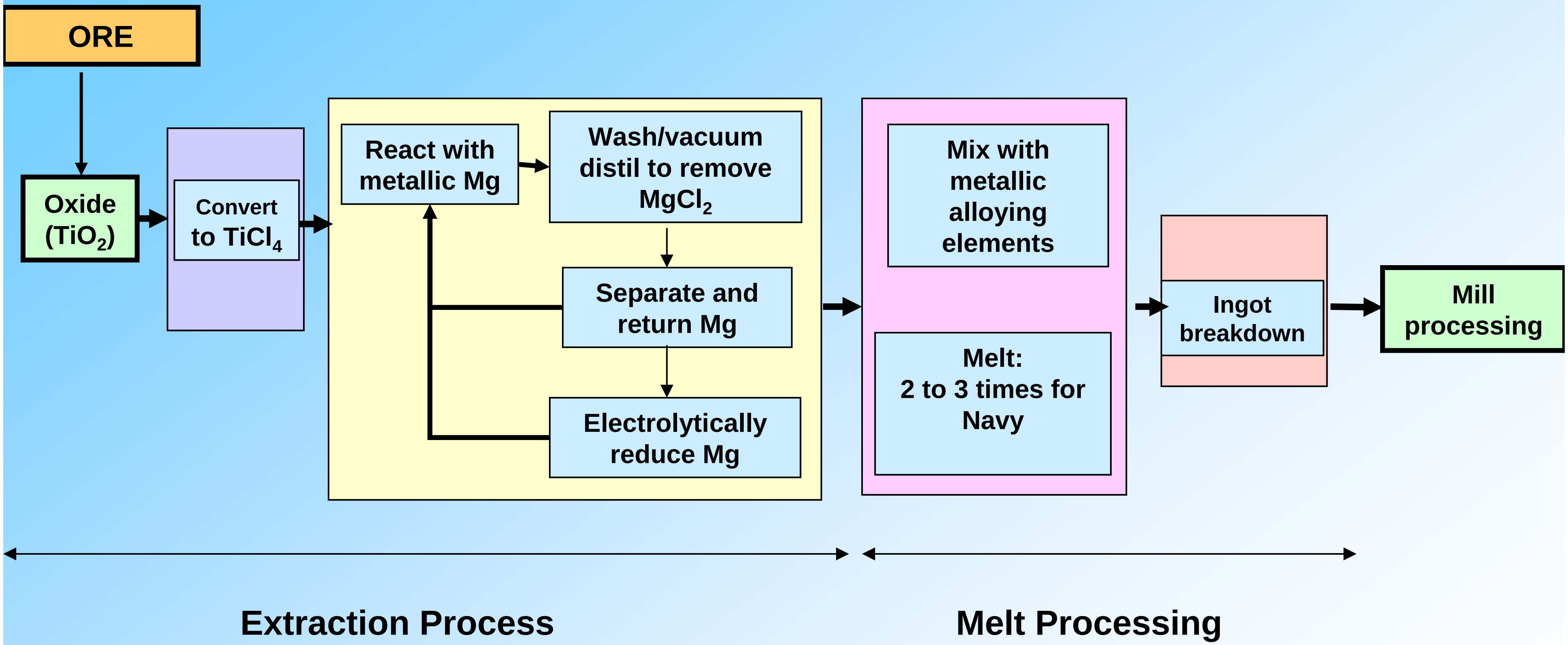
DARPA Titanium Initiative (DTi)

- DARPA/industry effort to develop more efficient processes in titanium ore extraction

Issue:

- Kroll process has been used since the 1940's to refine ore to titanium metal. Labor and capital intensive, accounting for ~38% of plate production cost.

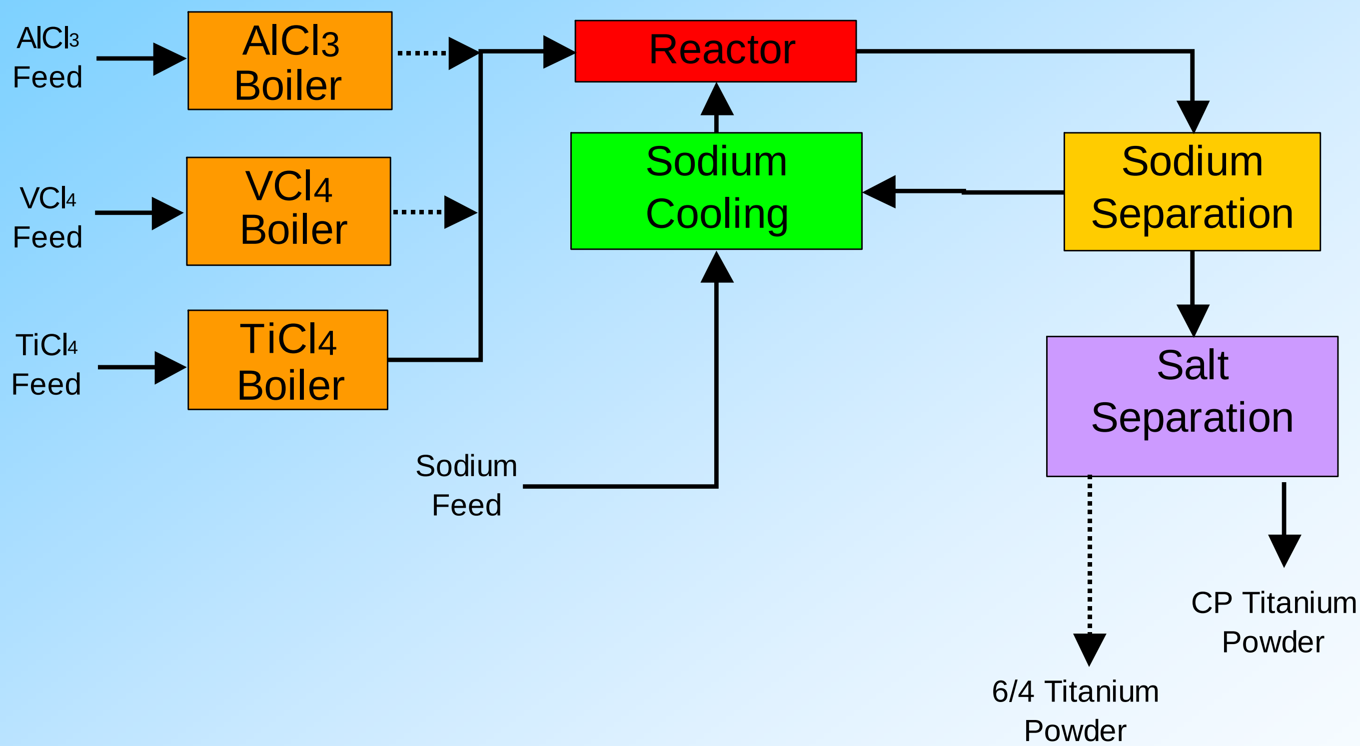
DTi - Titanium Production



DTi – Extraction Methods

- Two electrolytic reduction processes:
  - Reduction of porous TiO_2 cathode in a molten calcium chloride electrolyte to produce porous Ti
  - Reduction of solid TiO_2 anode in a mixed halide electrolyte to form powder
- Two chemical reduction processes:
  - High temperature fluidized bed to convert $TiCl_4$ to Ti powder or granules
  - Reduction of $TiCl_4$ with liquid sodium in low temperature reactor to produce Ti powder

DTi - Armstrong/ITP Process



- ***Simple, continuous process that operates at low temperature. Significant cost reduction compared to conventional sponge.***

DTi - Status

- Ti-CP and Ti 6Al-4V powders from IPT were compacted and rolled to sheet thickness
- Analysis in progress:
  - Weldability
  - Chemistry
  - Hardness
  - Metallography

IPT Ti-CP and Ti 6-4 Strips

Single Melt Processing

- Air Force/Army/industry effort to develop more efficient melting processes to vacuum arc re-melting (VAR)

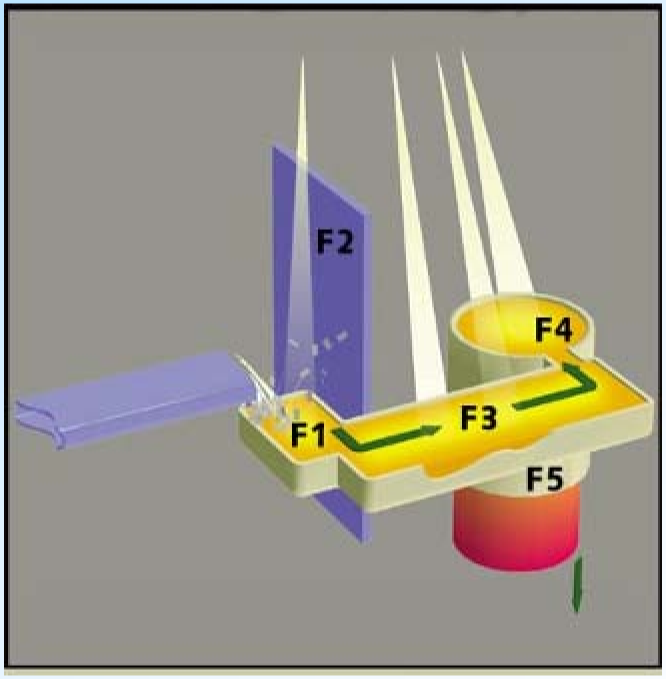
Issues:

- Multiple VAR is standard
- 2X-3X re-melt in vacuum for quality (no HDI's) - expensive
- Cylindrical ingot - difficult to process

VAR Ingot

Single Melt Processing - Electron and Plasma Beam

- EB and PAM
  - Lower cost
  - Semi-continuous
  - Rectangular ingots suitable for rolling into sheet and plate
  - Additional sources of feedstock (including scrap)
  - HDI-free billet



Schematic of EB Process

Single Melt Processing - Properties

- Single-Melt PAM versus Double-Melt VAR Ti 6Al-4V Forgings

Material	YS (ksi)	UTS (ksi)	%EL	K_{IC}
PAM 0.16% O	132-133	140-141	14-15	61
PAM 0.20% O	134-138	143-146	15	50
PAM 0.24% O	141-142	150-151	14	40
VAR 0.17% O	128-131	139-140	16-17	54
ASTM B381, Gr F-5	120	130	10	-

- ***Higher tensile and yield strengths and slightly lower elongation compared with 2XVAR***

Superplastic Forming and Diffusion Bonding

- Navy/Army/industry effort to develop SPF/DB process for low cost manufacturing of doors

Issues:

- 50,000 ship doors using 1950's design and DH-36
- Heavy and difficult to manipulate
- Major maintenance issue

SPF/DB - Status

- Demonstrated feasibility of process
- Design modeling in progress
- Contract to produce Ti 6-4 and Ti-5111 doors for evaluation

Hydrostatic Testing

SPF/DB Ti Door Installed on DDG-51

Welding Processes

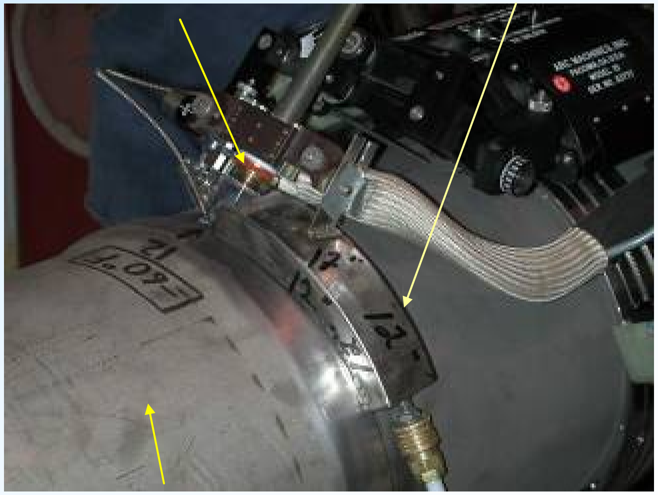
- Higher productivity welding processes to weld large structures in a <u>shipyard environment</u>
  - Flux-cored arc welding
  - Friction stir welding
  - Pulsed gas metal arc welding with waveform control

Titanium Fluxes

- ONR/industry effort to develop a titanium flux-cored arc welding technology for Ti-CP alloys

Issue:

Interstitial contamination reduces the ductility and toughness of titanium welds. Precautions to minimize contamination potential are a major contributor to high welding costs



Ti Fluxes - Formulations

- Fluxes
  - CaF_2 based
  - Reagent grade purity

Chemical Composition, wt %

	Formula P-A	Formula P-B	Formula C
CaF_2	85	45	70
NaF	1	--	1
BaF_2	--	7	--
LaF_3	--	20	--
SrF_2	--	28	--
MgF_2	--	--	15
$BaCl_2$	14	--	14

Ti Fluxes - Wire Drawing Feasibility

- Drawing
  - 0.160-inch OD to 0.055-inch OD, 22 dies at 5 mil reduction each
  - No intermediate annealing
  - Demonstrated reduction to 0.052-inch OD
  - Wire breakage, 30-40m lengths

Drawing Die

Wire Coils

Ti Fluxes - Feasibility

- GTAW with Ti-CP grade 2 flux-cored wire:

Formula P-C:
70%CaF_2 + 1%NaF +
15%MgF_2 + 14%$BaCl_2$

	C	Fe	O	N	H
Formula P - A	0.03	0.13	0.161	0.003	0.0072
Formula P - B	0.03	0.14	0.243	0.006	0.0065
Formula P - C	0.03	0.12	0.203	0.007	0.0129
Base Metal	0.03	--	--	--	--
ASTM B265 Gr.2*	0.08	0.30	0.25	0.03	0.015

Titanium Fluxes - Status

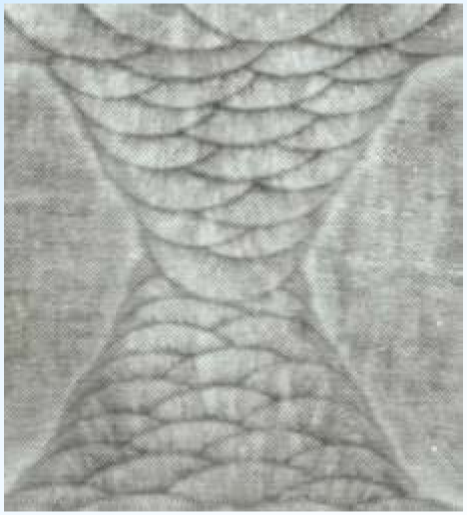
- Cormet contract for Ti-CP grade 2 flux-cored wires
  - Delivery scheduled for Feb 06
- Produce and evaluate Ti CP weldments:
  - Chemistry
  - Hardness
  - Mechanical properties

Friction Stir Welding

- ONR/contractor effort to develop friction stir welding of up to ½-inch thick Ti-5111 in the flat position

Issue:

GTAW is the only currently used process for shipyard welding of titanium. Low deposition rate, coupled with filler metal intensive joint designs, contributes to high welding costs



GTAW of 2-Inch Thick Titanium

FSW - Benefits

- Fewer passes
- Minimal joint preparation
- Environmentally-friendly and safe (no fume, arc, or spatter)
- Solid state – minimal distortion
- Minimal post weld clean up
- Reduced post weld inspection (no porosity or lack of fusion)

NSWCCD Friction Stir Welding/Processing System

FSW – Ti-CP Properties

Material	YS (ksi)	UTS (ksi)	%RA	%EL
AWM – double V	70.8	75.8	53.6	19.6
AWM –single V	67.3	72.15	62.1	16.7
Base Metal	45.87	62.75	58.3	28.9
ASTM B265	40-65	50	--	20

- ***Work in progress to investigate effects of texture and microstructure on properties***

Pulsed Gas Metal Arc Welding

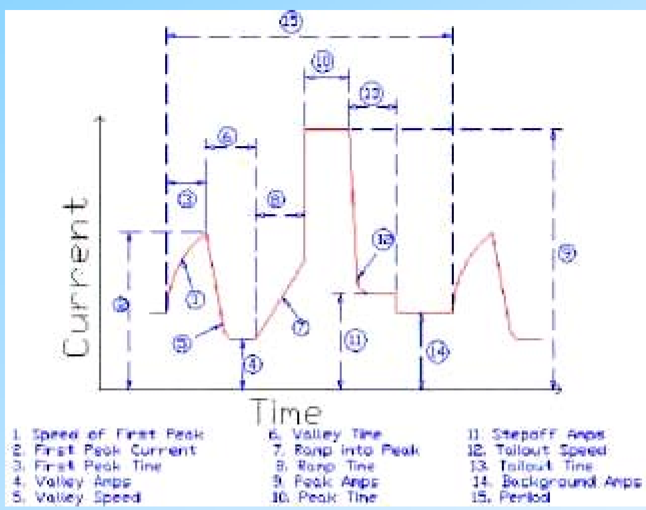
- ONR/contractor effort to develop pulsed gas metal arc welding process for all position welding of large structures

Issues

- Limited to flat position
- Low productivity of GTAW contributes to high welding costs.
- High heat inputs promote distortion of welded components

P-GMAW - Status

- Upgraded software and installed waveform algorithms
- Fabricated weldments in Ti-CP grade 2 plate
- Evaluation of mechanical properties in progress



Double Pulse Waveform Definitions for Wave Designer 2000

Ti-CP Weldment Produced with Double Pulse/Droplet Waveform

Plate/Weld Properties

- Optimize fatigue, ductility, toughness of welded structures and ballistic resistance
  - Laser peening for surface modification

Laser Peening

- ONR/contractor effort to develop laser peening of selected Ti alloys for improved performance

Issue:

Surface finish influences service life. Surface flaws or area of high stress concentration exposed to tension will experience a shorter service life under cyclic loading.

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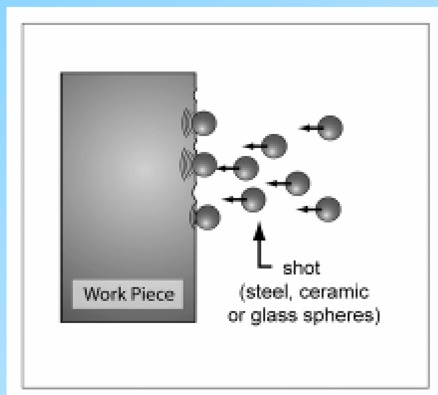
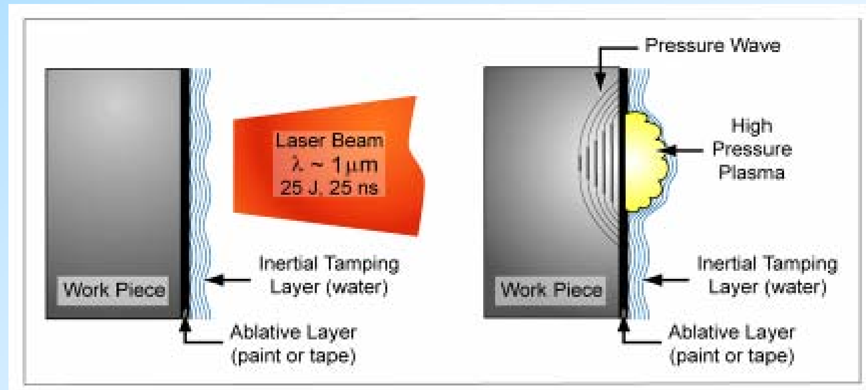
Laser Peening - Description

- **Extension of conventional shot peening**
- **High intensity laser induces deep residual compressive stresses in material**



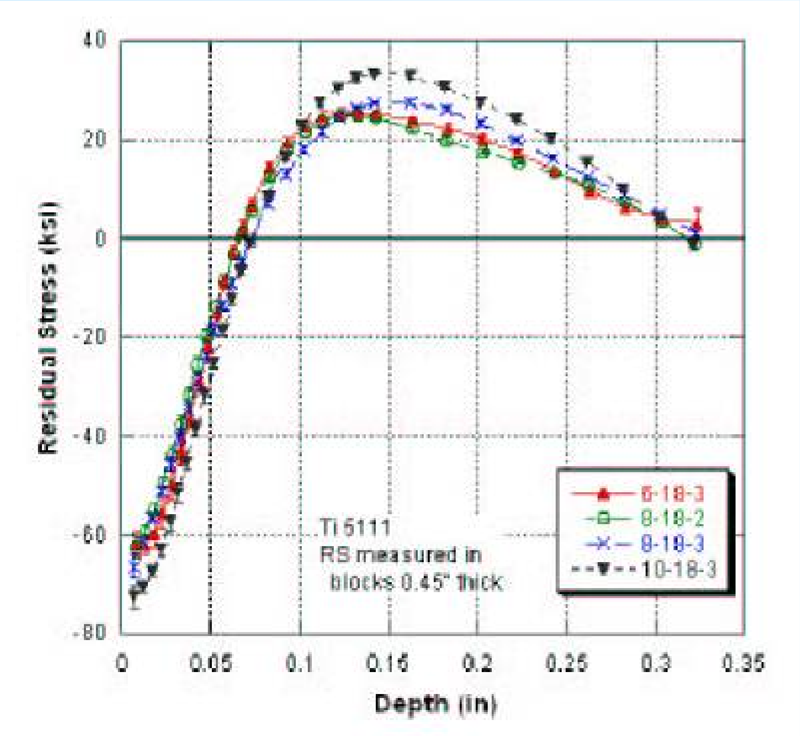


Laser Peening Process

- **Residual stresses are influenced by processing parameters**
  - Laser's power
  - Laser pulse duration
  - Number of pulses
  - Confining medium and absorptive layer

Laser Peening -Ti 5111 Application

- Produces high level of compressive stresses
  - 32 ksi, ~40% of typical 0.2% off set YS of 85 ksi for Ti-5111
- Applied to1.0-in thick weldment made with Ti-5111 filler wire by GTAW
- Machined 4 point bend fatigue coupons
- Peening at MIC and fatigue testing planned at UC-Davis



Summary

- Current applications are limited by high fabrication costs
- New opportunities exist for titanium to enhance structural efficiency of Navy ships for increased payload, range and stability
- Development and optimization of low cost plate, filler materials and welding processes is required to support increased usage